Strategic management of CO2

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Strategic management of CO_2: A scalable model for CCS in decarbonised societies

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ABSTRACT

In future decarbonised energy systems, residual carbon emissions require strategic planning and management. In environmental management, an evaluation of carbon removal considering local geographic frameworks is needed. This paper introduces a scalable and adaptable model for evaluating the economics and geography of future carbon capture and storage (CCS) configurations across geographical scales, covering capture, transport, and storage of carbon. The model is applied to the North Denmark Region, showing that future energy production carbon sources will be concentrated in Thisted and Jammerbugt, while industrial sources remain in Aalborg and Rebild municipalities. Carbon transport configurations, including truck, pipeline, and shipping are assessed, for the carbon to be stored in onshore and offshore geological storages. The regional scale findings suggest that pipelines and onshore storage provide the most economical configuration. However, a sensitivity study using a smaller geographical scope indicates potential for optimising carbon transport by evaluating both carbon volume and distance. The paper discusses how the model's flexibility and scalability enable the integration of alternate cost components, thereby supporting the calculation of the carbon repurposing potentials, including carbon capture, utilisation, and storage (CCUS) configurations.

1. Introduction

The excess of carbon dioxide (CO_2) is the primary cause of global climate change and ocean acidification (IPCC, 2022). Effective environmental management is a top priority worldwide. However, despite the climate mitigation efforts, not only have fossil fuels and carbon emissions tripled worldwide since the mid-1960s but peaked in global energy related CO_2 emissions in 2022 (IEA, 2023; IPCC, 2023) with 35.7 billion metric tons of CO_2. Though the emission growth rate slowed over the last 20 years, CO_2 emission projections estimate an increase of 15%, if the global energy consumption increases by 34% by 2050 (U.S. Energy Information Administration, 2023). This implies that current climate targets are falling short of the objectives for the near future. Countries worldwide are, therefore, part of agreements that commit to national emission reduction strategies as part of a magnified effort to limit global warming to 1.5 °C above preindustrial level (IPCC, 2023; IRENA, 2022). More than 70% of the total emissions (Ritchie et al., 2020) are attributable to how energy is produced, and climate response is therefore highly focused on the energy sector. Hence, most decarbonisation strategies include an energy transition into more renewable generation and sector coupling strategies, which exists under the umbrella term of Smart Energy Systems (Lund et al., 2017). Recent energy system studies (Connolly et al., 2016; Das et al., 2023; Ferrada et al., 2023; He et al., 2021; Lund et al., 2022; Luo et al., 2021; Mathiesen et al., 2015; Thellufsen et al., 2020), advocate for carbon reduction by replacing fossil with renewable energy production aided with carbon removal strategies.

However, while emission reduction is the primary target of the green transition, CO_2 is utilised in industrial processes e.g., food and chemical industry (Al-Shargabi et al., 2022; Kim et al., 2022; Wang et al., 2021), and at the same time, CO_2 is seen as potential raw material for synthetic or electrofuel (e-fuel)production displacing fossil fuel demand from hard to abate sectors, i.e., industry and transport. Therefore, decarbonisation shall not only reflect how to stop the use of fossil fuel, but also add an element of carbon management, focusing on achieving net-zero emissions across all sectors. The goal is thus both to reduce emissions and utilise carbon in the most effective way within the system. This includes carbon reduction or avoidance, and carbon removal strategies including biological, geological, and technological carbon sequestration. To reach such decarbonisation in entire energy systems will depend on local and strategised efforts that overcome the challenges and complexity of

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Abbreviations

CCS	Carbon Capture and Storage
CCUS:	Carbon Capture, Utilisation, and Storage
CHP	Combined Heat and Power
CO_2	Carbon dioxide
GIS	Geographic Information Systems
kTPA	kilo tonnes per annum
MTA	million tonnes per annum
OPEX	Operating expenses
PCC	Post-combustion capture
CAPEX	Capital expenditure
WtE	Waste to Energy

unique yet highly interrelated geographical contexts.

Distinct geographies offer biological carbon sequestration management potentials for climate mitigation which is investigated in land (Paul et al., 2023; Ravaioli et al., 2023), forests (Chen et al., 2007; Gogoi et al., 2022), and water bodies (Carr et al., 2018). Geospatial methods already build on the nexus between environmental management and sustainable energy (Ding et al., 2023), showing useful for resource management decision support, and planning practices (Simão et al., 2009). Similarly, energy system analyses focus on redesigning the energy system where it is more apparent that carbon sinks, i.e., capture and utilisation, or geological storage will play a significant role in the energy transition (Lund et al., 2022a,b). Current technologies are used for carbon capture and utilisation depending on whether the carbon is capturable or uncapturable at the facility scale. Emissions from the residential and service sector, forestry, municipal and agriculture waste, and transport are biologically captured today and can be captured through large scale direct air capture (DAC) in the future. Stationary sources such as industrial and power generation facilities can use carbon capture (CC) technologies for posterior use (CCU) or sequestration (CCS). When the post-capture carbon is used, this is referred to as direct air capture and utilisation (DACU), and carbon capture, utilisation, and storage (CCUS) technologies (Dziejarski et al., 2023). The technology readiness level (TRL) of most capturing technologies is between TRL6 and TRL7 (pilot plant and demonstration), while transport and storage technologies are between TRL7 and TRL 9 (demonstration and commercial), and non-Enhanced Oil Recovery (EOR) utilisation is in TRL6 (pilot plant) (Bui et al., 2018). Within the scientific community, however, CCS technologies meet criticism for their high investment costs (Kearns et al., 2021), and life cycle assessment implications resulting in increased emissions (Cuéllar-Franca and Azapagic, 2015), prompting efforts towards efficiency improvement (Ozkan et al., 2022) and increased capture rate (Dods et al., 2021).

CCS uses various types of technologies for source capture such as post-combustion, pre-combustion carbon capture or oxy-fuel combustion systems (Global CCS Institute, 2021). For carbon utilisation, technologies include the carbon usage after capture in industrial processes by converting it into plastics, concrete, or biofuel (Storrs et al., 2023; Chen et al., 2022). Hence CCUS will enable the use of carbon and CO_2 as a resource to create chemicals and fuels in hard-to-abate sectors, while CCS has a role to play either in capturing and storing CO_2 from non-renewable industrial processes, in offsetting sectors that cannot avoid emissions or in achieving negative emissions from biogenic resources. The literature suggests that CCS technologies are not new but are increasingly recognised for their role in achieving climate goals in the near future. This is particularly true for certain regions with sufficient geographical resources for CCS infrastructure.

To understand the complexity of how CCS potentially can play a role in the decarbonisation of society and how it interacts with the energy system, it is important to systematically investigate the geographical aspects of the infrastructure. The success of CCS depends on three important factors that need to be considered and investigated from a geographical aspect. These include.

1) The availability of point sources: While DAC can be an option for the future (Fasihi et al., 2019), most carbon capture projects are currently based on point sources. These point sources will significantly change in the transition towards a smart energy system that will experience less energy production from combustion and increased renewable energy.
2) The availability of storages: This includes access and proximity to onshore and offshore CO_2 geological storage options.
3) Alternatives of transport infrastructure between source and storage. This includes investigation of trucks, ships, and pipelines to understand the dynamics of different transport options and their economic impact.

Geography and location are key to these factors and a few studies have investigated CCS from a geographical point of view; but overall, they see several limitations. These include that the models are not replicable, only focus on certain limited scopes, and most importantly, are based on current CO_2 estimations and do not include future potential changes to the energy system, such as the decrease of non-biogenic carbon and the increase of biogenic carbon. Furthermore, fossil carbon sources will simply cease to exist as they are not compatible with future decarbonised societies.

European CO_2 infrastructure is investigated in the H2020 Gateway project (Jakobsen et al., 2017), where a pilot model is developed using both quantitative and qualitative criteria. More localised European CO_2 transport corridors are investigated in North-west and Central Europe, where CO_2 point sources are clustered in an optimised network (Morbee et al., 2012; Neele et al., 2011). In North America biorefineries with CCS (BECCS) are assessed nationally (Johnson et al., 2014), and a scalable CCS model is developed for the Californian state (Middleton and Bielicki, 2009), both using spatial modelling. In China, assessments use source-sinking matching models disregarding the geographical dimension of the analysis (Wu et al., 2022), or non-spatial energy, economy, and environmental models for assessing CO_2 mitigation potentials with CCS (Zhu et al., 2015). More recently, The Joint Research Centre of the European Commission has performed European scale assessments (Tumara et al., 2024) that include other sources than just power generation sector CO_2 point sources. These studies highlight important messages at a regional level but miss out on potential connectivity opportunities through clustering entire geographical contexts.

On a national scale in Europe, cost-effective infrastructure design using Geographic Information System (GIS) tools are developed in the Netherlands to model CCS integrated into energy system analysis (van den Broek et al., 2009). Here, regions are connected to sinks as a proxy location for CO_2 point source clusters and pipeline transport is in focus, disregarding other transport options that might benefit economically. In the Dutch sector of the North Sea, clusters of gas fields for CO_2 sinking are located, and the investment of the infrastructure is assessed anticipating a total national combined CO_2 supply (Wildenborg et al., 2022). Karlsson et al. perform CCS cost assessments for future biogenic and non-biogenic CO_2 mitigation in the Swedish industrial context without identifying alternate CCS configurations for infrastructure optimisation (Karlsson et al., 2024). Similarly, the Swiss mapping for CCS design via pipeline of waste-to-energy CO_2 point sources has been carried out, including the storage option of the Norwegian Northern Lights project (Northern Lights Consortium, 2023) for network optimisation (Becattini et al., 2022). While CO_2 clusters play a crucial role in identifying CCS potential, clustering methods overlook the specific location of the CO_2 supply. Additionally, network optimisation methods that connect geographical points using Euclidean distances undermine the objective of a geographical assessment. The location of CO_2 resources at a supply level enables for the assessment of alternatives for carbon transport and storage on different geographical scales, which is highly relevant for the planning of CCS.

In Denmark, CCS and CCUS have been included in future models of smart energy system analysis with both storage and utilisation based on the principle of CCS for a final abatement step and not for fossil use mitigation (Lund et al., 2022). A CCS pilot case connecting a coal-fired power plant and an onshore storage was studied but the project was abandoned due to insufficient legislation and lack of public acceptance in 2011 (Dalhoff et al., 2011). At present, there is a high focus on CCS and CCUS technologies, especially after Danish projects have been categorised as Project of Common Interest (PCI) for the European Union, and The Danish Energy Agency has launched tendering processes for permits for the exploration and storage of CO_2 in five onshore areas, three of which have already been awarded i.e., Gassum, Rødby, and Havnsø (Energistyrelsen, 2023d). Regional studies on CCS involve capturing CO_2 emissions from the highest emission point sources within a region (Greenhub Denmark, 2023), while some other focus on specific pilot industrial cases, such as those within the cement industry (Aalborg Portland, 2023) with ongoing scale-up planning (Energy Supply, 2023). Overall, there is insufficient research from the scientific community within CCS planning in the country, and as such, this study derives from it.

2. Scope

The cited literature serves two main purposes. It is an inspiration for the development of a model in which the identified gaps re addressed, and for the identification of a case study to which the model can be applied. Gaps identified include the decarbonisation assessment of future carbon sources including industry and power generation, the use of a bottom-up approach in GIS analysis that maintains a level of detail across scales, and the need for scalable models to assess alternate CCS configurations at different geographical scales. For the case study in this paper, European studies at regional scale highlight Denmark and Norway as key geographies for a European CO_2 transport network. Both countries are shown as potential CCS frontrunners in Europe due to their geological storage capacity, proximity to ports, and to point sources when compared to other European countries (Kouri et al., 2017). A particular region of interest is the Northern Denmark Region, highlighted in European studies as a principal part of CO_2 corridors, connecting Scandinavia, the North Sea, and the rest of continental Europe (Morbee et al., 2012; Tumara et al., 2024). The region is also relevant at a national level because it hosts the single largest Danish CO_2 emitter i.e., Aalborg Portland, a coal fired Combined Heat and Power Plant (CHP) that will be phased out i.e., Nordjyllandsværket, as well as the most extensive foreseen development of bioenergy production (Food & Bio Cluster Denmark, 2020) which has a primary role in a decarbonised energy system in Denmark (Lund et al., 2022). Furthermore, various ports as well as onshore and offshore storages are located in and within proximity of the region.

On this basis, this paper proposes a bottom-up geographical methodology for assessing CCS infrastructure. It describes a method to develop a cost model that incorporates individual components of the downstream management of future carbon sources: capture, transport, and storage. Depending on the CCS configuration, options are provided for both the transport and storage components in the model, such as transport mode and onshore, offshore, or intermediate storage. Thus, the model is designed to provide a geographical routing and a techno-economic assessment for the chosen CCS configuration. This approach is independent of the geographical focus, making the model scalable. Results and analysis are included for the case study of the North Denmark Region, with a geographical sensitivity analysis to test the model's scalability. This is performed on a refined scale in the Thy-Mors area, a part of the region used to investigate the impact of varying CO_2 volumes and distances in transportation options. The model does not incorporate the utilisation component for a CCUS assessment; however, it enables Power-to-X scenario analysis at an energy system level. The CCS configurations presented for the case study are utilised at the regional geographical level for assessing strategies that consider full decarbonisation of energy systems in Ref. (Bang et al., 2024).

3. Methodology and data

This section comprises two sections: the first describes the methodology for developing the geographical CCS cost model, and the second provides details on the case study CCS configurations. Mixed methods are used, including data handling and compilation using tabular and geographic databases in Geographic Information Systems (GIS) for the identification of location and further spatial analysis of CO_2 point sources. The software used for the spatial analysis is ArcGIS Pro 3.1.0 (ESRI, 2023a) from the Environmental Systems Research Institute (ESRI). ArcGIS geoprocessing tools and additional built scripts using ArcPy and Python languages were used to code the automation of the cost assessment of which the infrastructure spatial characteristics are the key indicators. The geographical delimitation of the case study is the North Denmark Region. However, the method is flexible and generically designed to be used and adjusted independently of the geographic scope. A visualization of the models' inputs and output is shown in Fig. 1.

3.1. Geographical CCS cost model

As seen in Fig. 1, the main objective of the model is to generate total annual costs and geographical routing for CO_2, allowing for a techno-economic comparison of CCS configurations. To accomplish this, the geographical cost model accommodates four segments: the capture (CC), transport (CT), final storage (CS), and intermediate storage (CIS) of CO_2, which are all assessed in a corresponding spatial framework. A methodology to incorporate the four segments of CO_2 downstream management is developed with the steps depicted in Fig. 2. Subsequent sections elaborate on each of these steps.

3.1.1. Mapping CO_2 point sources

To map CO_2 point sources, both location and availability are considered, departing from the current state to an overlook into the future. The mapping methods are subdivided into characterization and estimation of CO_2.

3.1.1.1. Characterization of CO_2 point sources. To characterize the point sources, this study considers the type of CO_2, the point source emission category, and the capture technology utilised. The analysis targets future biogenic and non-biogenic CO_2. Biogenic carbon is defined as the CO_2 emitted from processes where biomass or organic compounds are converted into fuels, while non-biogenic carbon is the CO_2 emitted by the combustion of fossil fuel when directly burned to generate energy. The capture type considered is the most mature capture technology, post-combustion CC (PCC), in which the emitted CO_2 is captured from exhaust or flue gas stacks after the CO_2 is emitted and released into the atmosphere. Narrowing down the scope with these considerations, attention is directed towards flue gas emissions from electricity and heat production plants, as well as industrial facilities. Each emission point within these sectors undergoes systematic categorization and mapping, identifying them as potential future CO_2 point sources for CCS configurations. Other categories of CO_2 emitters within the commercial, residential, agricultural, or forestry sector are considered not fitting for PCC technologies and are out of the scope of this study. Hence, the four types of CO_2 point sources considered relevant for the study are.

1. Electricity and heat production plants
2. Waste incineration plants
3. Biogas production plants
4. Industrial facilities

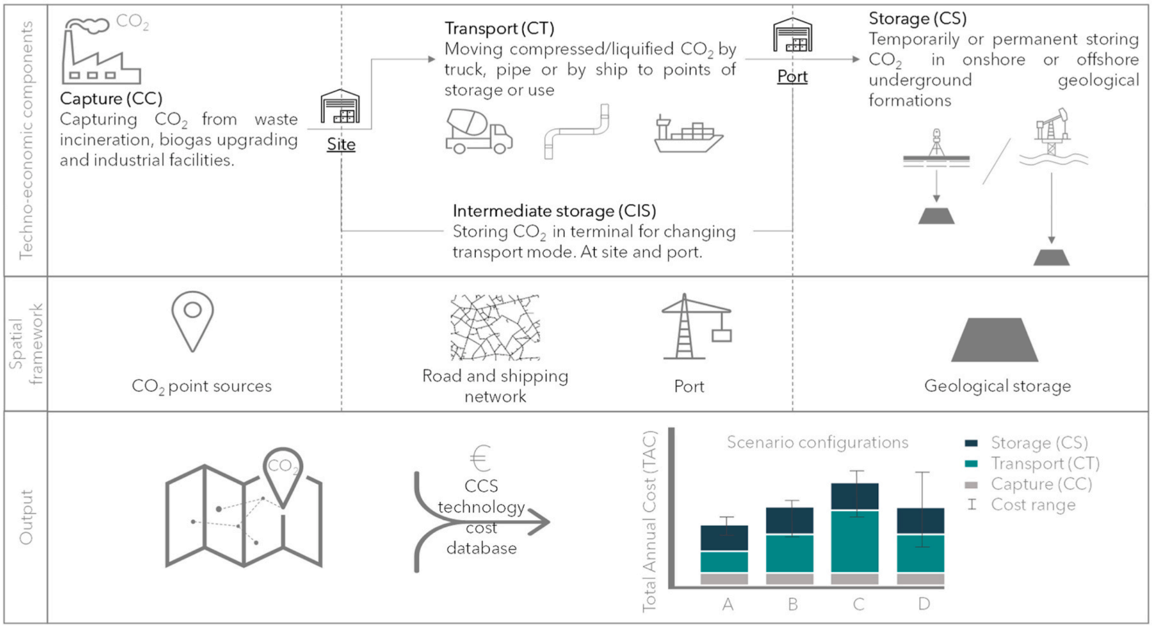

Fig. 1. Geographical CCS cost model: Components and output overview.

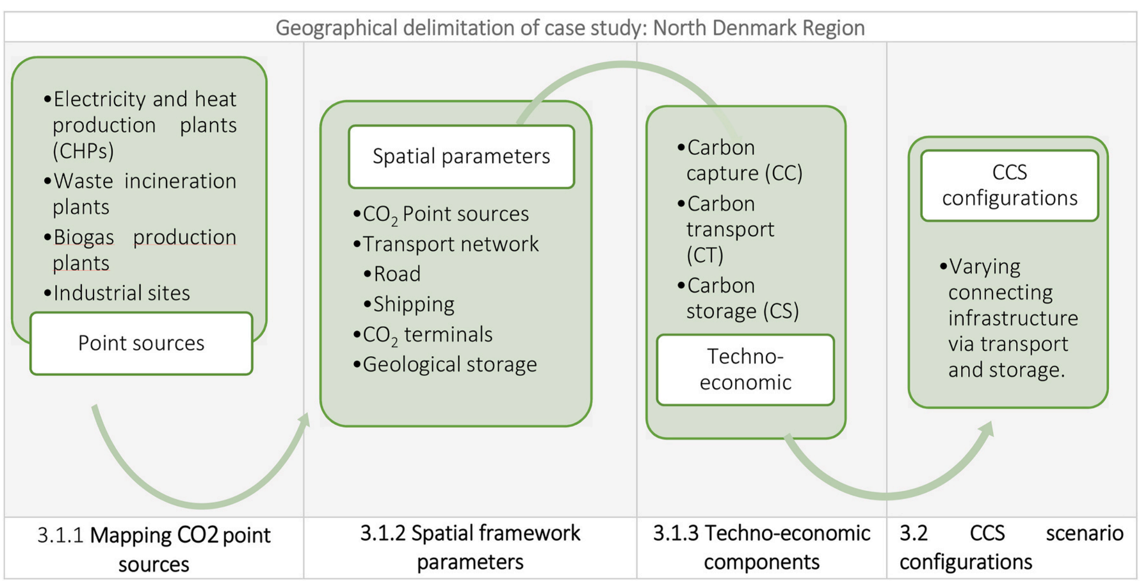

Fig. 2. Methodology overview and flow.

The data collection overview is shown in Table 1, with details on the databases and sources used for the CO_2 mapping. Once the categorised data sets were gathered, each facility's location was mapped by geocoding. The geolocation process for established facilities is done by proxy using facility address and facility name with geolocator algorithms in Python scripts, i.e., geopy, followed by a manual and visual cross-validation step. For the manual validation, place databases and satellite imagery from web mapping platforms such as Google Maps were employed, as well as public online business databases that serve as search engines for accessing information on facilities (Erhvervsstyrelsen, 2022). For planned facilities, namely future biogas production plants, online accessible and published maps from The Danish Energy Agency (The Danish Energy Agency, 2020; The Danish Energy Agency, 2019; The Danish Energy Agency, 2023a; The Danish Energy Agency, 2023b), and Greenhub Denmark (Greenhub Denmark, 2023) were used as a comparison point for manual verification of the estimated location of facilities.

3.1.1.2. Estimation of current and future CO_2. To project the future availability of CO_2, the assessment starts with evaluating current CO_2 and proceeds with its development based on potential impacts that can limit such CO_2 sources due to decarbonisation efforts. To accomplish this, this study develops a 2045 CO_2 scenario based on a possible future 100% renewable Danish energy system as part of a transition towards a fully decarbonised society. The baseline year for the assessment is set at 2022, and the future year has been chosen following the IDA's Climate Response 2045 decarbonising plan for Denmark (Lund et al., 2021), which is a robust studied scenario (Lund et al., 2022a) supporting a fully renewable future energy system as a pathway for Denmark to achieve 70% reduction in GHG emissions by 2030, aiming at climate neutrality by 2045 and climate positive by 2050. The scenario is hereafter denoted as IDA2045 and used as an example of a complete decarbonisation of the

Table 1
Data gathering overview for CO_2 point source mapping.

	Category	Name	Source	Year	Ref
1	Electricity and heat production plants	Energy producer census	The Danish Energy Agency	2022	Energistyrelsen (2023c)
2	Waste incineration plants				
3	Biogas production plants	CCUS Cluster North Jutland	Greenhub Denmark	2022	Greenhub Denmark (2023)
		List of biogas producers in Denmark	The Danish Energy Agency	2021	Energistyrelsen (2021)
4	Industrial facilities	CCUS Cluster North Jutland	Greenhub Denmark	2022	Greenhub Denmark (2023)
		European Pollutant Release and Transfer Register	European Environment Agency	2021	European Environment Agency (2020)
		The Central Business Register	The Danish Business Authority	2022	Erhvervsstyrelsen (2022)

Danish energy system.

The scenario helps identify factors that can limit or promote CO_2 emissions, such as expanding biogas renewable capacity and phasing out fossil-fuelled capacity. For power generation, IDA2045 includes reduced waste incineration and a commitment to sustainable biomass utilisation through bioenergy expansions amid identified opportunities for the increase of locally and globally traded sustainable biomass sources, supported by previous studies in Denmark (Lund et al., 2022) and Europe (Victoria et al., 2020). For the carbon reduction in industry, estimations are based on projected levels of industrial electrification. The principles that guide the assessment of each type of CO_2 source are summarised

Table 2
Considerations for CO_2 estimation by point source category.

	Category	Capture rate[c]	Baseline 2022 CO_2	2045 CO_2
1	Electricity and heat production plants	90%	Estimated using total annual fuel consumption from (Energistyrelsen, 2023c) and CO_2 emission factors from (Energistyrelsen, 2023a)	Neglected. CHP biomass phase out[a]
2	Waste incineration plants	90%		50% CO_2 emission reduction[a]
3	Biogas production plants	100%	Using a chemical composition (CH_4/CO_2) 60/40 vol% in raw biogas (Li et al., 2017)	2.13-fold increased CO_2 emission[a]
4	Industrial facilities	90%	Composite estimation using categorised fuel consumption per industry and branch (Huang et al., 2015), and CO_2 emission factors (Energistyrelsen, 2023a).	CO_2 emission reduction estimation from the electrification processes related to innovation in industrial production[b]

[a] IDA decarbonising plan for Denmark (Lund et al., 2021).
[b] Green Industry Analysis Project (Energistyrelsen, 2020).
[c] Capture rates in flue gas stacks and biogas upgrading systems (Cordova et al., 2022; IEAGHG, 2019; Li et al., 2017).

and presented for both the baseline in 2022 and 2045 in Table 2, and more detailed considerations are presented in Appendix A: Estimation of future CO_2.

Carbon capture technologies remain capital intensive (Jha et al., 2021; Kearns et al., 2021), which makes it economically challenging for small CO_2 sources to partake. Considering the risk of locked-in solutions preventing smaller sources from decarbonising, point source sizing criteria is applied. Literature shows CCS potentials assessed including emitting sources of at least 40 kTPA (Greenhub Denmark, 2023), 50 kTPA (Energistyrelsen, 2023b), and 100 kTPA (State of Green, 2022) of CO_2. However, to maintain the defined geographical scope of this study, the sources considered need to respond to the largest emitters at national level, yet keeping smaller sources to be able to shape CCS potential configurations. Therefore, the study lowers the threshold and includes emission sources equal to or exceeding 10 kTPA of CO_2. The identified CO_2 point sources are then integrated into a geodatabase, forming part of the rest of the spatial framework parameters of the model, which are described in the following.

3.1.2. Spatial framework parameters

The spatial framework includes the geographically identified infrastructure relevant for CCS configurations. The data and tools utilised for creating the framework are defined and explained as follows.

1. Point sources: Defined as the locations of the CO_2 point sources and mapped in Section 3.1.1 where the sources are characterized, and CO_2 is estimated, providing location and volume.
2. Transport network: Defined as the trucking, piping, or shipping routing to calculate the transport length of CO_2 from point sources to terminals and from terminals to permanent geological storage. The Danish Road network (Dataforsyningen, 2023) is used to route CO_2 via truck and pipe, while Euclidean distances are used to route the CO_2 offshore. The road network is used in the model due to the absence of an actual network in the area, serving as the best available proxy to simulate a layout that considers land restrictions. The spatial analysis tools to assess the routing are the Network Path Planner (ESRI, 2023c) and Closest facility Analysis (ESRI, 2023b) geoprocessing tools from ESRI. The path planner optimises the pipeline network routing, while the closest facility analysis creates the shortest trucking routing between two points.
3. Terminals: Defined as the closest location to CO_2 point sources to a potential CO_2 intermediate storage where transport mode-switching is needed. The region's main ports are considered as terminals when CO_2 is to be transported by ship i.e., Port of Aalborg, Port of Hanstholm, Port of Hirtshals, and Port of Frederikshavn.
4. Geological storage: Defined as the location of onshore, nearshore, or offshore underground formations that are deemed suitable for CO_2 storage. These geological structures can be unexplored sites and depleted oil and gas fields with substantial capacity available. The Geological Survey of Denmark and Greenland (GEUS) describes a list of potential CO_2 geological storage structures in Denmark (GEUS, 2020). From the report, the reservoirs listed in Table 3 are included as part of the spatial framework of the case study.

Table 3
Geological structures suitable for CO_2 storage from (GEUS, 2020).

Structure name	Theoretical storage capacity (Million tonne CO_2)	Type	Spatial proximity in case study
Hanstholm	1333–3441	Nearshore	33 km from Hanstholm port
Siri Canyon (Cecilie, Nini and Siri)	150–500	Offshore depleted oil field	236 km from Hanstholm port
Gassum	412–777	Onshore	Central part of Danish Basin

A compilation of the spatial framework parameters in the North Denmark Region is shown Fig. 3.

3.1.3. Techno-economic components

The costs used are derived from the Danish Energy Agency database for Carbon Capture, Transport, and Storage (The Danish Energy Agency, 2023c). The parameters are adapted to harmonize and translate into the spatial framework of the model; this adaptation is performed for each of the elements of the techno-economic assessment: the capture (CC), intermediate storage (IS), transport (CT), and storage (CS) of CO_2.

For each element, specific capital expenditures (CAPEX) as well as variable and fixed operational (OPEX) expenses that amount to the total cost are annualised in 2020 EURO (€) using present values from the catalogue and documented in the supplementary material as raw input for the model. The cost components taken from the database are described in Appendix B: Detailed TAC cost components. Appendix C: Techno-economic components further explain the calculation for each cost projections.

Based on each projection, a composite cost model is developed. Each element cost is expressed in a yearly cost as a function of the amount of CO_2 captured, transported, or stored, and the geographical distance over which the CO_2 is transported. Collectively, the sum of each cost component output from Eqs. (2)–(5) yields a total annual costs (TAC) in Eq. (1). Each TAC consists of CAPEX calculated as annuity payments given the technology lifetime and a discount rate of 3% (García-Gusano et al., 2016) using the annuity equation in Eq. (6), plus an annual OPEX.

$$TAC = TAC_{CC} + TAC_{CT} + TAC_{CS} + TAC_{CIS} \quad [€ / year] \tag{1}$$

Where:

$$TAC_{CC} = CAPEX_{CO_2} * annuity + \left(OPEX_{fixed/variable}\right)_{CO_2} \tag{2}$$

$$TAC_{CT} = CAPEX_{CO_2,distance} * annuity + \left(OPEX_{fixed/variable}\right)_{CO_2,distance} \tag{3}$$

$$TAC_{CS} = CAPEX_{CO_2} * annuity + \left(OPEX_{fixed/variable}\right)_{CO_2} \tag{4}$$

$$TAC_{CIS} = CAPEX_{CO_2} * annuity + \left(OPEX_{fixed}\right)_{CO_2} \tag{5}$$

And:

$$annuity = \left[\frac{r}{1 - (1 + r)^{-n}}\right] \tag{6}$$

With:

$CO_2 = yearly\ captured, transported\ or\ stored\ CO_2$

$distance = geographical\ distance\ of\ CO_2\ transport$

$r = discount\ rate\ expressed\ as\ a\ decimal$

$n = technological\ lifetime\ in\ years$

Additionally, to incorporate cost uncertainty in the study, the 2030 costs are used as the base cost while 2050 lower and 2050 upper price developments are applied as cost thresholds, and a ±20% where costs are unavailable. These thresholds work as a cost range for all calculated TAC and are included in the model output. An overview of this cost composition can be seen in the schematic bar chart in the model output in Fig. 1.

3.2. CCS scenario configurations

The CCS configurations are potential scenarios for collecting, transporting, and storing the CO_2. While the capture of CO_2 from point sources is fixed, each pathway utilises different transportation modes, and storages within the spatial framework described to provide an assessment for the case study. Table 4 presents the scenario configurations for the model, detailing the alternatives for each cost component. There are three scenarios: A and B are modelled for nearshore and offshore storage, while C includes onshore storage.

4. Results and analysis

The results are first shown for the estimation of future CO_2, followed by the outputs from the techno-economic assessment of the proposed CCS scenario configurations. Finally, the model is tested on a smaller scale, in a sub-area of the region, to assess CO_2 volume and distance in the choice of transport.

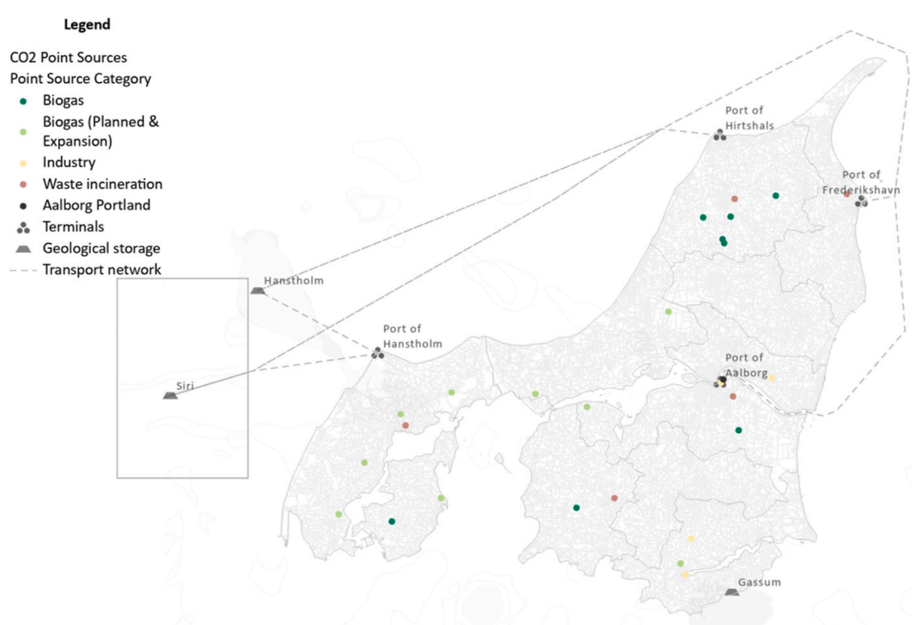

Fig. 3. Spatial framework for CCS scenario configurations in the North Denmark Region.

Table 4
Geographic cost model scenario configurations. The table is organised from left to right, starting with the cost components and to the specific scenarios on the right.

CCS Cost Component	Scenarios			
	A (Truck + Ship)	B (Onshore pipeline + Ship)	C	
			(Onshore + offshore pipeline)	(Onshore pipeline)
Capture (CC)	All CO_2 point sources			
Intermediate Storage (CIS)	At site	–	–	
Transport (CT)	Truck	Onshore distribution and transmission pipeline	Onshore distribution and transmission pipeline	
Intermediate Storage (CIS)		Nearest port		–
Transport (CT)	Ship	Ship	Offshore pipeline	–
Permanent Storage (CS)	Nearshore and Offshore	Nearshore and Offshore	Nearshore and Offshore	Onshore

4.1. 2045 CO_2 projected availability

The baseline year for the CO_2 availability assessment in this study is 2022, and the projected future availability of the resource is made for 2045, assuming a fully decarbonised Danish energy system scenario that accounts for the associated carbon reduction. The study area is the North Denmark Region, where electricity and heat production, waste incineration, biogas production, and industrial facilities are mapped. Hence, this includes biogenic and non-biogenic CO_2. In 2022, a total of 6.47 MTPA CO_2 is estimated with 5.88 MTPA of potential capture with available technology. Close to 90% of this potential is found within 6% of the facilities responding to categories larger than 10k TPA in the region, as seen in Fig. 4, which argues positively for the filtering out of smaller emitters suggested in the methodology section.

Following the sizing criterion and the four principles formulated departing from the IDA 2045 scenario in Table 2, the future CO_2 reduction is pictured in Fig. 5. As expected, a significant decrease of 64% occurs due to the fossil phase-out, which eliminates the CO_2 emissions from Nordjyllandsværket, reduces the emissions from waste incineration, and includes the electrification of industrial processes. The CO_2 quota from current and planned biogas production remains constant,

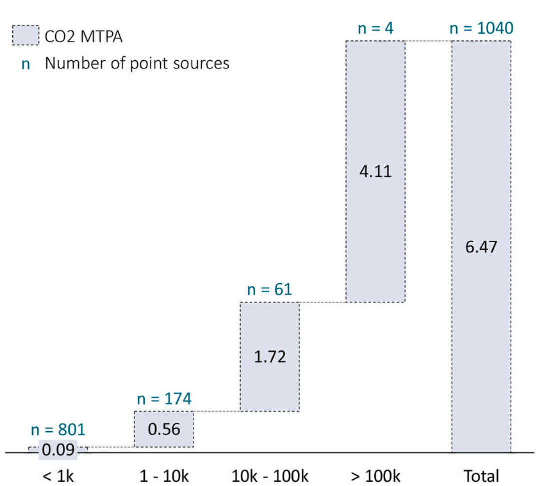

Fig. 4. Baseline calculated CO_2 (MTPA) in 2022. The facility's yearly emission range is shown on the x-axis.

and its expansion increases the future CO_2 capture potential by 28% after fossil fuels are phased out. Regarding the spatial distribution of CO_2, most of the current biogas production may be placed is in the northern part of the region in Hjørring Municipality. In contrast, the planned biogas plants are mainly located on the west coast in Thisted and Jammerbugt municipality. The industrial point sources are located primarily in Aalborg and Rebild municipality. However, Aalborg Portland, located in the city of Aalborg, is the largest single CO_2 emitter, with around 50% of the total CO_2 potential capture. The symbology shows the ungrouping emission sources in Fig. 5, and the geographical distribution of the sources is shown in Fig. 6 to add a location and magnitude perspective.

4.2. CCS configurations in the North Denmark region

This section shows the geographical output of the model given the spatial framework of the case study, which includes the carbon potential of the 45-point sources aggregated in 27 facilities. Figs. 7–10 show the model outputs as geographical routing for each CCS scenario configuration. For the trucking in scenario A, all the nearest ports are considered to route the CO_2 to final storage i.e., Port of Aalborg, Port of Hanstholm, Port of Hirtshals, and Port of Frederikshavn. The spatial analysis estimated trucking distances ranging from 0.3 to 53 km, 19–51 km, 18–28 km, and 5–23 km for each port, respectively. The ports of Aalborg and Hanstholm emerge as the most intensive both in terms of the quantity of CO_2 transported, and the trucking distance required.

For scenarios B and C, which include onshore and offshore pipelines, a transmission line connecting the ports is assumed to optimise the network. Additional distribution pipes following the road network connect to this transmission line. A total of 194 km in transmission and 267 km in distribution pipeline are calculated. Scenario C adds a transmission line extension connecting the original transmission to Gassum for onshore storage. The latter increases the transmission by 65 km and reduces the distribution pipeline length by 48 km. The offshore piping length towards Hanstholm is 33 km, and 236 km to Siri, from Hanstholm port, the closest port to both offshore storages.

Based on the routing options, the model outputs costs per configuration, which are compared in Fig. 11. The most cost-effective configuration is achieved with a pipeline to the onshore storage Gassum: Scenario C (Gassum). The most considerable partial contribution to the total costs are the capture and the storage, fluctuating between 29% and 47%, and 22%–52% of the total TAC, respectively. Transport with trucking in Scenario A represents 90% of the cost of pipeline transport in Scenario B, when accounting for intermediate storage in Scenario A. This suggests that trucking becomes ineffective and costly as CO_2 is transported individually to the different ports, while pipelines centralise capacity and shorten transport distances. When comparing the same storage destination, the cost difference between the transport with truck and pipe in Scenarios A and B is within ±12%. However, the total shipping cost is primarily reduced in Scenario B since the CO_2 is centralised for shipping in one port against distribution in all four ports in Scenario A, adding ≈520 km of extra shipping. Transport to nearshore storage in Scenario C (Hanstholm) by pipe shows nearly equivalent costs to transport in Scenario B (Hanstholm) by ship. However, pipeline costs escalate as distances to offshore storage increase, as per comparison in Scenario B and C (Siri). Onshore storage in Scenario C (Gassum) is 27% below the average cost among all configurations due to minor savings in intermediate storage. Still, lower costs respond to optimised onshore pipeline transport and lower onshore costs than nearshore and offshore storage. From the figure, it can also be seen that the costs of intermediate storage are modest throughout the scenarios at site and port, representing 2–3% of each TAC.

4.3. Geographic scaling for CCS configurations

The configurations shown provide insights into the pathways that

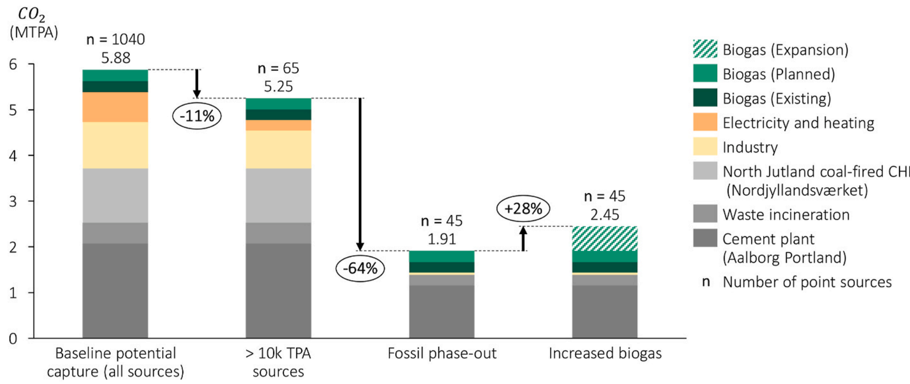

Fig. 5. Estimated CO_2 (MTPA) potential for capture in 2045. The x-axis shows the step criteria for estimation.

Fig. 6. Map of categorised point sources and estimated CO_2 potential capture by 2045 in the North Denmark Region.

could shape CCS infrastructure in the North Denmark Region. The cost outputs show fewer flexibility options for the capture and storage components than for carbon transportation. Hence, the remaining questions pertain to the degree of optimisation achievable in transport costs, the role of geographical distances, and the CO_2 volumes in this optimisation. This section is dedicated to assessing the model's transport sensitivity by focusing on a different geographical scale to determine its impact.

Using the techno-economic parameters from Section 3.1.3, the cost per unit of CO_2 transported across the different transport modes is plotted in Fig. 12. CO_2 volume brackets from 50 to 500 kTPA are included to draw attention to the changing costs over distances and facilitate the comparison. The three plots try to group similar behaviours seen in the CO_2 volume brackets. As the volume of CO_2 transported increases, not only does the unitary cost of transport decreases but the transport modes become more cost-competitive over shorter distances due to cost advantages reaped by economies of scales. More interestingly, for CO_2 volumes up to 50 kTPA, trucking appears to be the least costly option up to ~350 km, while pipeline transport becomes more economical beneficial beyond this threshold. As the pipeline cost curves level off, the shipping curve falls intercepting the pipeline curves at shorter distances.

These visualizations indicate approximate distances at which different CO_2 transport modes are more cost favorable. Focusing on this metric, the most competitive transport modes are plotted for distinct CO_2 volumes where a break-even distance point is marked. This point should be understood as the distance at which the costs of CO_2 transport balance out, and a pivotal point after which the most economical transport mode switches. The crossing points can be seen in the two plots of Fig. 13 that are separated to avoid visual saturation. For the lower CO_2 volumes, i.e. 10 to 100 kTPA, the break-even shrinking distances are observed, having its peak at 10 kTPA when trucks switches to ships, and the lowest at 100 kTPA when trucks switches to pipelines. For the largest CO_2 volumes, break-even distances increase, however, not on the scale they decrease at smaller CO_2 volumes. The unitary break-even cost of transport decreases drastically as CO_2 volume doubles, reaching a peak of 92% unitary cost reduction from 50 to 100 kTPA.

These findings suggest that with the intended quantity of CO_2 and transportat distances, the break-even distances can serve as a tool to design the downstream of CCS configurations. The developed model is deployed at a smaller geographical scale within the North Denmark Region to assess the cost sensitivity in more detail. Using the administrative borders to limit the geographical scale, the Thy-Mors area situated along the west coast of the region, containing the Port of Hanstholm are deemed suitable for this purpose. The municipality have representative transport distances, and smaller CO_2 volumes, which according to

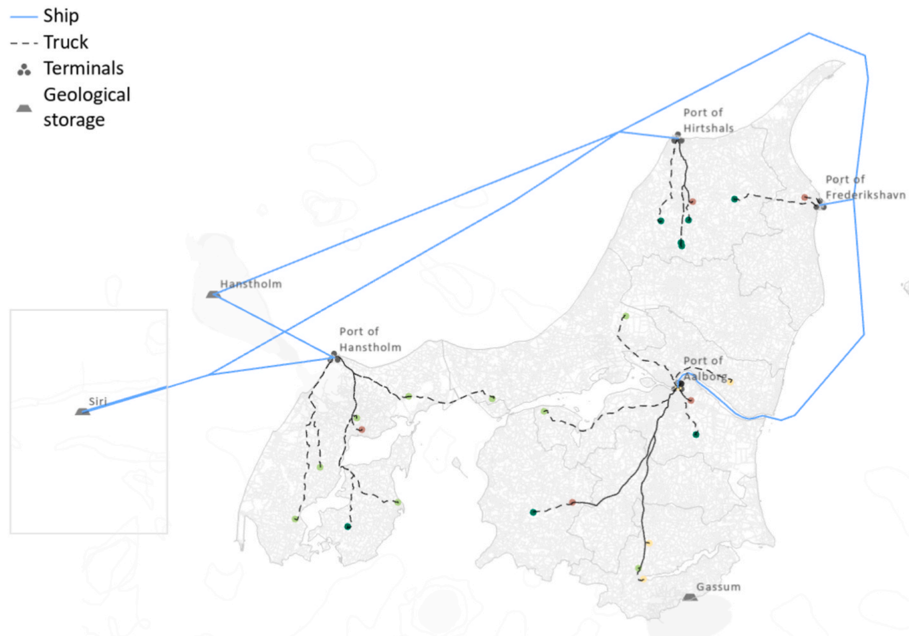

Fig. 7. Scenario A: Offshore storage geographical routing via truck and ship.

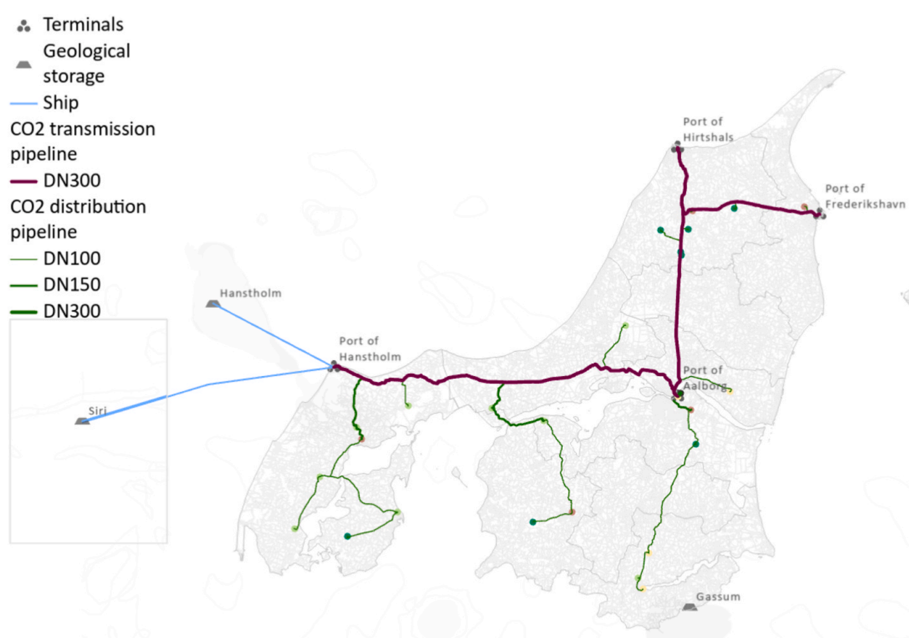

Fig. 8. Scenario B: Offshore storage geographical routing via pipeline and ship.

the regional outputs will result in higher unitary costs. The estimated CO_2 total of 301 kTPA that can be transported in the municipality correspond to roughly 12% of the regional CO_2 estimated in 2045. The break-even distances are then utilised in a mixed scenario, involving partial trucking to intermediate storage and partial piping thereafter, see geographic representation in Fig. 14. This sensitivity is to assess saving costs, particularly concerning the transport TAC. The cost comparisons to the mixed scenario are presented in Table 5, highlighting the most significant transport cost reductions when compared to piping, and an average of ≈7% with the other more competitive configurations. When total costs are compared, the mixed configuration reaches an average cost reduction of ≈9%.

5. Discussion

The authors acknowledge that the CO_2 capture potential projected in 2045 is a result expected CO_2 by 2045 as part of a specific scenario where the central assumption is to achieve a fully decarbonised energy system. Various uncertainties are inherited from this overarching scenario, which is an envisioned pathway for reaching the transition, as well as the estimated carbon reduction emissions. According to the overarching IDA2045 scenario, a 5 MTPA sink estimate with CCS and biochar is necessary. The carbon sink is deemed essential as compensation for other sectors' emissions, such as agriculture and industrial processes, that are difficult to bring to CO_2 neutrality. Supposing the transition envisaged in this scenario fails or is delayed in cutting carbon

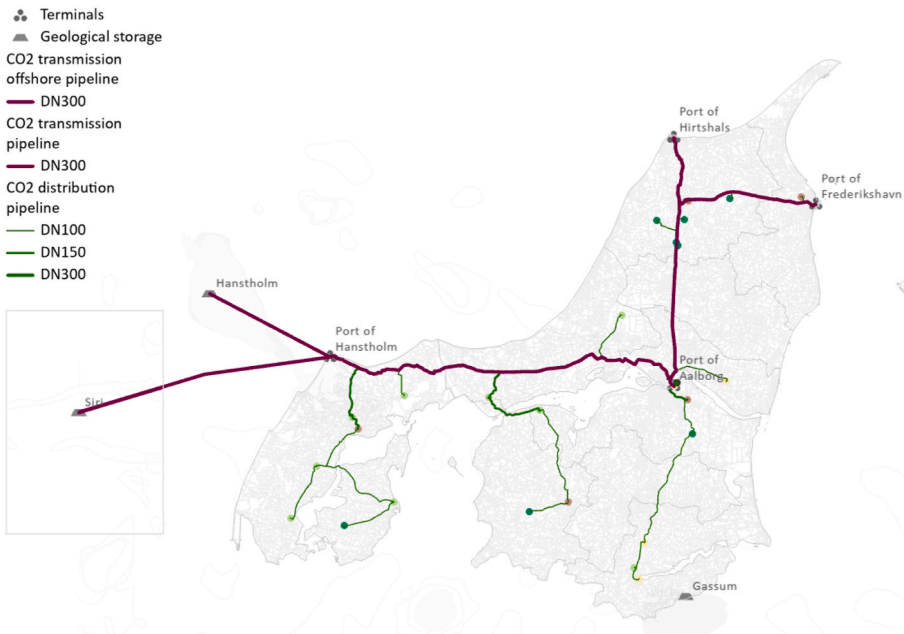

Fig. 9. Scenario C: Offshore storage geographical routing via pipeline.

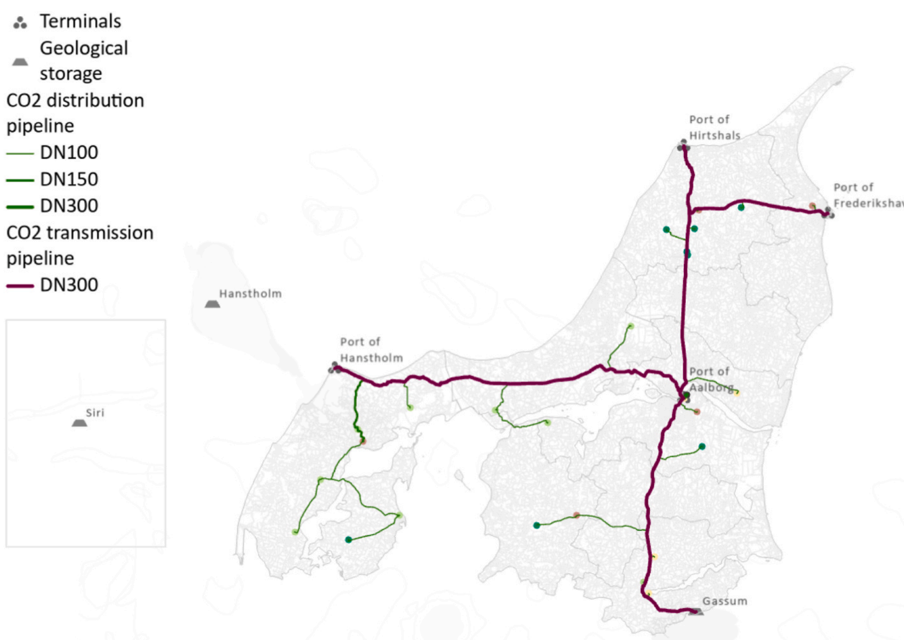

Fig. 10. Scenario C: Onshore storage geographical routing via pipeline.

emissions, the CO_2 potential capture will persist, exacerbating the need for further sinking mechanisms to reach a fully decarbionsed future. This can come from other capture technologies such as DAC or additional deployment of capture technologies from point sources that will rely on well-identified carbon sources as input for their assessment. Alternative considerations regarding the availability of CO_2 sources in the future could significantly influence the evaluation of CO_2 available in 2045 i.e., external carbon sources, emission sizing delimitations. However, the accounting of CO_2 is not regarded as the primary focus in this study; conversely, the modelling of geographical CCS pathways for CO_2 is, why the estimation is taken as a point of departure for the model development and usage.

Likewise, the assessment of CO_2 availability from point sources was methodologically categorised and generalised, while each facility will in fact experiment differently with emission change. As an example, the North Denmark Region's CHP plant, 'Nordjyllandsværket' will be decommissioned in 2028, with current efforts targeting an earlier transition into renewable generation by 2025 (Aalborg Forsyning, 2023). The biogas expansion from IDA2045 is assumed uniformly for all biogas plants in the region, which hardly resonates with reality as early biogas adopters are less likely to expand in the short-term future compared to preestablished biogas producers. The latter should also consider the competition for feedstock availability and deploy a sustainability perspective in a broader perspective. Out of the point sources, the estimations made for the industrial facilities are the most indeterminate given the uncertainty on the scale of electrification of each type

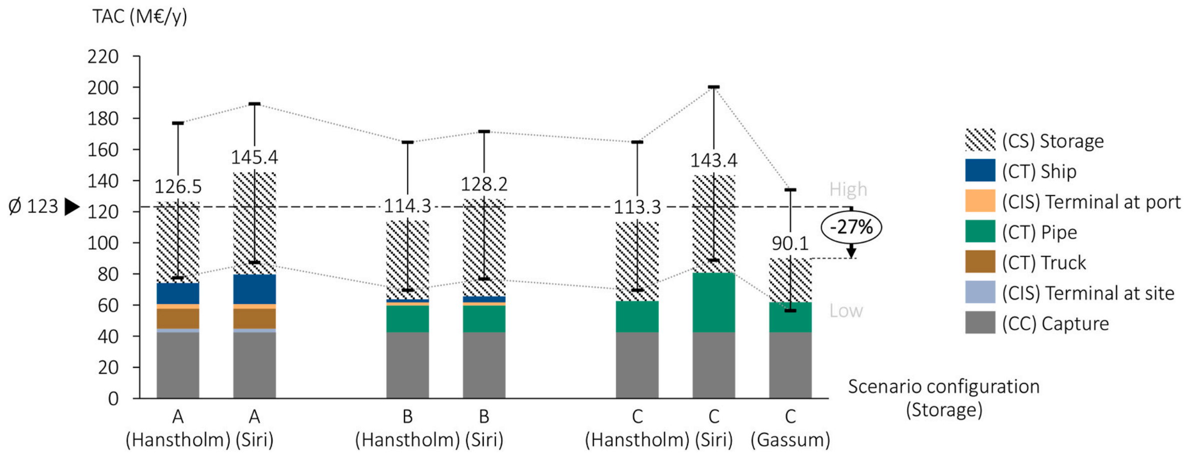

Fig. 11. Total annual cost scenario comparison showing a base cost in stacked bars and high and low uncertainty cost ranges through error bars. Symbology colours are showing cost components per configuration.

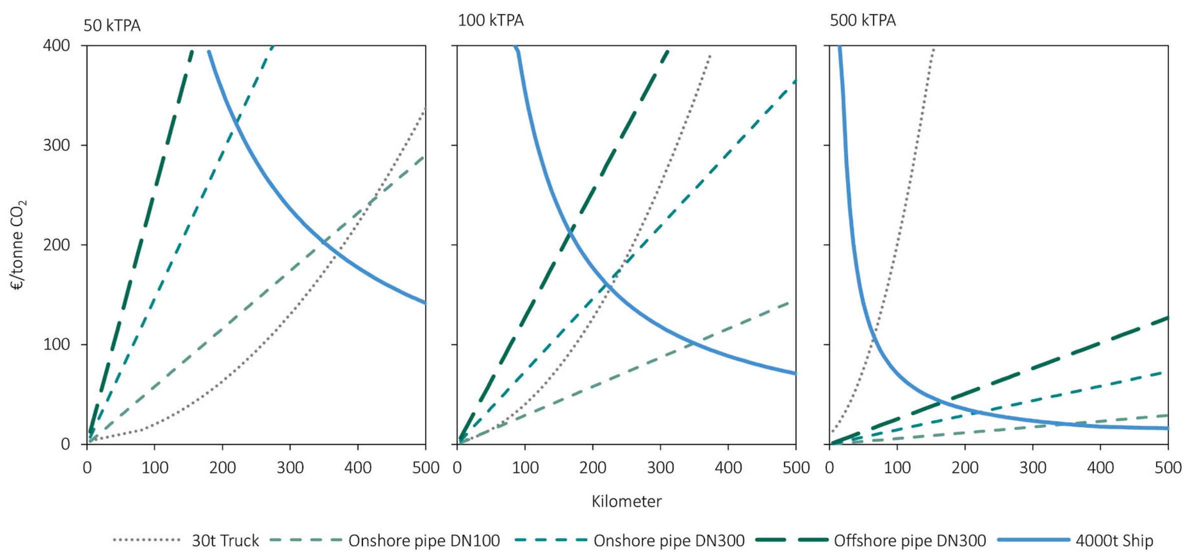

Fig. 12. Cost curves representing the unitary cost of CO_2 transport across distance by transport mode. Upper labels show specified CO_2 volumes. Note the shared vertical axis.

of industry and how fast that would be accomplished. This study approximates this electrification by assuming that a share of energy and carbon-intensive industrial processes requiring high temperature and pressure would be electrified, replacing biomass and waste incineration fuel requirements on the energy production side.

Waste incineration and industrial facilities are the non-biogenic carbon sources considered, while biogas production represents the biogenic carbon of the total CO_2 estimated. In total, the calculated biogenic carbon fraction for capture in the study is 41% in 2045, while the remaining is non-biogenic. While the emissions from non-biogenic CO_2 sources accounted are the ones that can be captured from flue gas stacks, a point for discussion is the applied understanding of sustainability for the biogenic CO_2 included in the analysis. While the metric assessment is out of the scope of the paper, the sustainability of the carbon aimed to be captured plays a key role when considering carbon sinking strategies. A sustainability assessment of bioenergy crops and feedstock as part of the bioenergy system must be considered, primarily provided the expected increased capacities. Securing closed carbon loops guarantees the avoidance of extra emissions and ultimately results in effective CCS technologies removing and reusing the carbon that would otherwise be released into the atmosphere. Looking at carbon sinking as the goal, however, a valid point for discussion is the relevance of only biogenic carbon. A tonne of CO_2 from biogenic and non-biogenic sources is quantitatively equal yet does not represent the same carbon, nor is it within the same domain of the carbon cycle. Initiatives like CCS should be considered strategic and incorporate qualitative assessments should be made to ensure deployment effectiveness, aligning with the overarching objective of reducing emissions from the production side. This approach can prevent perpetuation or delays in fossil operations, counteracting transition efforts and aid with current policies that focus on biogenic CO_2 sources for e-fuel production (Renewable Energy Directive, 2018).

The type of capture considered for the CO_2 point sources in the study focused on PCC and excluded other capture technologies such as Oxy-fuel CC technologies. While PCC is deemed appropriate for the type and magnitude of sources, it could be worth assessing oxy-fuel capture for significant CO_2 emission sources such as cement production plants and large biomass boilers. However, the cost of the required air separation unit and energy requirements might represent limitations against PCC. At the same time, all CO_2 capture potential is assumed to have a purity level appropriate for CC available technology. The capture considers a 98% vol CO_2 purity before post-cleaning on a wet basis and >99.95 % vol on a dry basis. The assumption is unrealistic in all flue gas, and the chemical processes to achieve higher purity levels through

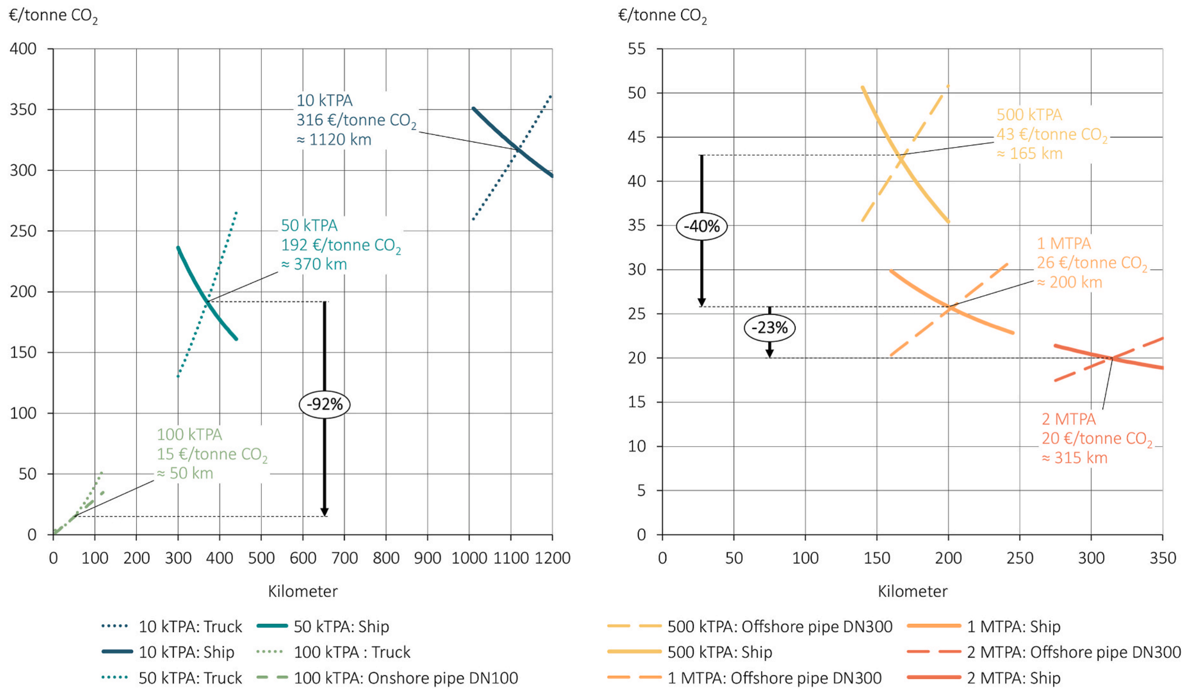

Fig. 13. Break-even transport distances across transport modes. Note the distinct scale in both axis.

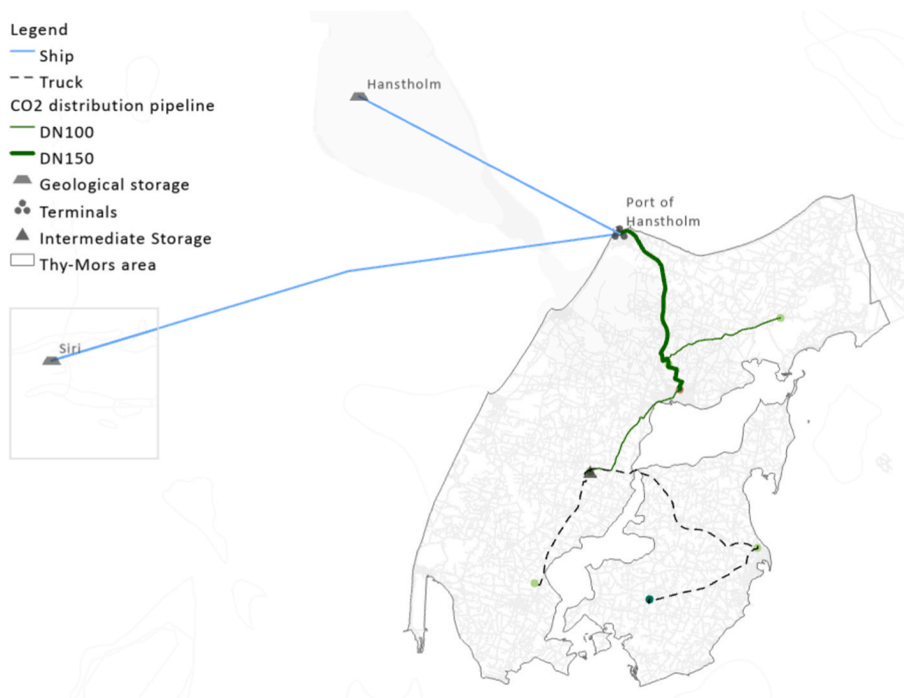

Fig. 14. Geographical cost model applied to the Thy-Mors area using break-even points for CO_2 transport.

purification units are not considered any further in the analysis performed. It is essential to state that extra purification units in CC processes can double or three-fold the costs in diluted gas streams versus highly concentrated ones, which can impact the calculated TAC in the capture and transport costs as CO_2 properties change - See Section 4.2. On the other hand, the 90% capture rate used is considered conservative, as up to 95% is expected to be feasible after 2030 due to technological developments. The last aligns with the expected CC CAPEX cost decrease by 55% by 2050, in PCC (Kearns et al., 2021).

In brief, a projection of carbon reduction is made, and variations of the CO_2 availability in 2045 are expected. The considerations taken for the projections are described and discussed as the objective of the CO_2 scenario is to calculate and locate the CO_2 from point sources to be used in the geographical cost model development. While a bottom-up approach is applied, other approaches could have been considered, such as the distribution of a national CO_2 emission by industry or share, which would have simplified the CO_2 estimation vastly. In the same way, taking the carbon storage capacity as the initial point, the transport

Table 5
Cost sensitivity utilizing break-even transport distance points for transport in mixed scenario. Note percentual difference in red.

Parameter	Storage	[M€/y]			
		Scenario			
		A	B	C	Mixed:
		Truck + Ship	Onshore pipeline + Ship	Onshore + offshore pipeline	Truck/ Pipe + Ship
TAC_{CT}	Hanstholm	3.5 −4%	3.7 −11%	4.5 −36%	3.3
	Siri	4.4 −3%	4.6 −9%	15.9 −275%	4.2
TAC	Hanstholm	16.91 −1.2%	16.85 −0.9%	18.88 −11.5%	16.70
	Siri	19.73 −1.1%	19.66 −0.8%	30.54 −36.1%	19.51

of CO_2 could have been tailored to reach such capacity. Additionally, the model assumes that space requirements for the capture are met in all point sources; an approach considering the geographical space requirements for CCS technologies could have benefited the feasibility of implementing capture plants. Therefore, while the approach exhibits some strengths and weaknesses, it is considered that the attempted scope targeted by assessing each CO_2 point source and its development towards 2045 provides a beneficial resolution for the techno-economic geographical assessment. This level of granularity represents additional flexibility when serving as an input for the cost model, as shown by the sensitivity analysis presented in section 4.3, where different geographical scales and CO_2 volumes for CCS are modelled.

Regarding the techno-economic assessment performed, as a relatively new technology for the Danish context, CCS cost estimations are updated regularly, introducing considerable uncertainty to the configuration's costs. In this study, this uncertainty is tackled by using the cost range with a low and high cap cost, resulting in a ±40% range from the base cost that reflects potential cost variations. The addition of certain cost components to this study can be an example of such variations, i.e., the liquefaction cost that has been equated to the compression cost at capture. Similarly, since the model only considers new investments in CO_2 transport, repurposing existing gas infrastructure could help reduce costs and align more closely with the lower cost estimates presented. The model also allows for the use of alternative networks, enabling the integration of new grid infrastructure or more accurate potential network layouts. A thorough investigation into the technical aspects of CO_2 pipeline transport is essential, especially given that the current Danish gas network operates at much lower pressures. This difference in pressure can impact CO_2 transport capacities at higher rates and increase the risk of condensation. The cost estimates presented thus are not the basis for the final investment decision; instead, they offer a geographical screening and a cost sensitivity analysis tool informing carbon management planning processes. In addition, the geographic focus of the outputs helps determining investment locations, serving as a starting point for discussing potential ownership distributions within the region. Here, the scalable bottom-up CCS model in this study can be a useful tool to include considerations on CO_2 into transitioning energy systems, particularly at the local planning level due to its resolution. As demonstrated throughout the study, the implementation of new technologies such as CCS and PtX is crucial for achieving climate targets. Location awareness aids in decision-making by assessing the impacts of ownership and cost distribution on a localised scale. The different CCS configurations analysed reveal potentials for investment costs, whether aggregated into fewer centralised schemes or dispersed across multiple decentralised stakeholder schemes. These schemes differ in their impacts, adding unique requirements and local value. Thus, the location and connectivity assessments shown through the maps provide valuable insights into future CCS developments, enabling the level of detail necessary for meaningful planning at various levels.

These initial CCS configurations provide essential hints for further exploring alternative scenarios with a wide range of options. While in the study, ports are conventionally considered placements for intermediate storage functioning as terminals from where CO_2 is shipped, identifying strategically located CO_2 clusters can offer alternative infrastructure placement. This could alleviate CAPEX and OPEX costs by creating decentralised CO_2 hubs that collect and transport higher CO_2 volumes. Other pathways to be explored could include connecting all large emitters or a connection from the Port of Aalborg to the Port of Hanstholm which are the closest to the largest emissions. Mixed configurations can include a southbound transmission pipeline from all large emitters down to the cheapest onshore storage Gassum, connecting most of the CO_2 point sources and buffering via truck the further ones for cost efficiency. Here, the longest routing distance would be the biogas CO_2 point sources located in Thisted municipality which could be monitored according to their development and competitivity against northern municipalities. These alternatives, however, should raise questions about perpetuating infrastructure around current CO_2 emission sources versus exploring alternate and perhaps more flexible infrastructure. The authors assert that variations to both cost outputs and configurations are foreseeable, especially as the scope narrows down, and CCS projects are explored with more contextualization.

For each configuration, the storage cost amounts to ≈50% of the TAC, which can be inferred as an argument for investigating CCUS instead of CCS, especially considering offshore storage, where storage cost is the highest. Although CCUS is out of the scope of this study, the model provides flexibility for the addition of cost components. This allows for future evaluations to compare the costs of utilisation versus storage. Another limitation of the study is the local CO_2 focus, which disregards opportunities with additional CO_2 imports that can be used to assess storage or utilisation. CO_2 imports could effectively reduce the unitary storage cost of CO_2. However, extra infrastructure related to the import has to be accounted for as intermediate storage at ports, and piping or shipping capacities are increasingly needed for final storage. National infrastructure costs, however, will remain towards the downstream of CO_2 collection to ports. While the geographical model developed provides a bottom-up approach for potential CCS infrastructure, the utilisation of the CO_2 requires a comprehensive understanding of the technology within the whole energy system, mainly as PtX is intricately linked to the electricity and the heating system to achieve sector coupling.

The cost sensitivity of the configurations is tested on a smaller geographical scale in Section 4.3. With the results provided, it can be said that the mixed configuration offers cost reduction potential but entail trade-offs and extra costs, notably the included costs for intermediate storage. Additional costs associated with the technical aspects of CO_2 transport, such as alterations in CO_2 phase requirements due to changing transportation modes, are not accounted for in the model. In the mixed configuration presented, incorporating an extra compression unit at intermediate storage would add extra infrastructure, as well as operational and land costs. Following the outputs from the sensitivity analysis, it can be said that using various forms of transportation can result in modest cost reduction as the optimisation of the downstream management of the CO_2 is reached. However, the addition of these modes involves logistic and operational requirements adding to the value chain complexity and final cost. It can also be seen that increasing the geographical detail aids in contextualizing and assessing local potentials as well as challenges within CCS configurations.

6. Conclusion

This study has mapped, characterised, and estimated future Danish CO_2 point sources, and a geographical CCS cost model has been developed and applied to the case study of the North Denmark Region.

Varying CCS configurations are designed to assess techno-economic and geographic routing feasibility. Adding to the analysis, mixed transport configurations have been investigated in the Thy-Mors geographical area as to optimise CO_2 downstream management and the implications of the findings are presented as a sensitivity analysis in the study.

By 2045, a total of 45 CO_2 sources in North Denmark will merge into 27 facilities, offering 2.45 MTPA for CCS. Different transport options are considered in CCS configurations, which yield an average total annual cost of €123M. The findings show potential in transport optimisation when higher resolutions are considered for the geographical scaling of the CCS configuration since both quantity and geographical location are driving factors.

To conclude, this study has yielded valuable insights into CCS strategies. By developing a bottom-up geographical cost model, the study not only presents a potential workflow for CCS configuration assessments but highlights the model flexibility for enhancements and usage in diverse geographical scales. The model's scalability represents potential for creating transition scenarios that are useful for energy planners at any level. The research additionally contributes with specific key messages and discussions related to carbon management that can be withdrawn for techno-economic tailoring and optimisation of storage and furthering the value chain towards carbon utilisation scenarios. CCS is one of the alternatives for carbon avoidance or removal, and the investigation of alternative technologies such as DAC can be considered in future research. Moving forward, CCS requires further assessment as a technology that complements strategies for energy transition such as energy demand reduction, sector coupling, increased renewable penetration, and the dynamics with other low-carbon and carbon-neutral technologies aimed at fully decarbonising energy systems.

CRediT authorship contribution statement

Diana Moreno: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Aksel Bang:** Writing – review & editing, Methodology, Conceptualization. **Steffen Nielsen:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Jakob Zinck Thellufsen:** Writing – review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122175.

Appendix A. Estimation of future CO_2

This section expands on Section 3.1.1 on the usage of the IDA 2045 scenario regarding the CO_2 estimation. The estimation for each of the CO_2 point sources categories considered for the study is elaborated here.

With varying biomass usages, the IDA plan accommodates a range of 4.5–5.6 MTA CC from waste incineration, bioenergy, and industry. Part of the carbon is allocated to CCUS as in e-fuel production through Power-to-X (PtX) which is added as flexible demands in large RES production periods. Both usages point out that both technologies, CCS and CCUS will come to play an important part of the energy matrix. Sankey diagrams for 2020 and 2045 scenarios of the Danish energy system can be seen in Figs. 15 and 16. The figures explain the use of primary energy through conversion to each end use demand and sector. Moreover, Fig. 17 incorporates a Sankey diagram illustrating insights into biomass utilisation, with a focus on CCS and CCUS potentials. In addition to the IDA2045 scenario, considered as the benchmark for evaluating the impacts on the availability of the CO_2 point sources within a 100% decarbonised energy system, supplementary considerations for industrial electrification are made. From here, four principles are formulated to guide the analysis, these are detailed and presented according to the type of CO_2 point source mapped in 3.1.1.

1.Electricity and heating production

IDA2045 emphasizes on the reduction on burning biomass in CHP systems but the continuing development of biomass in the form of biogas, thermal gasification, pyrolysis, and hydrothermal liquefaction (HTL) technologies. Offshore and onshore wind, together with PV deliver 70% of the total primary energy consumption in the energy system. Sector coupling allows for urban heating demands to be supplied through RES powered District Heating (DH) systems i.e., waste incineration, surplus heat, and geothermal energy, while far reach heating demands are converted to individual electric heat pumps supplied by a large development of solar thermal in rooftops. *Consequently, all fossil fuelled CHP plants are phase-out by 2045, meaning no CO_2 is accounted from these sources in the future.*

2. Waste incineration

Waste incineration has typically been used for CHP or heat production for DH systems. By 2045, waste incineration is reduced but remains fuelling DH systems, particularly using certain types of biomasses that are difficult to process in other facilities and the increase of recyclability and separation in waste streams. According to IDA2045, the technology can incorporate CC to flue gas, and there will be additional industrial processes on which solid biomass or biomethane can be burned for such requirements. *As an approximation to this vision, the baseline emissions related to the projected waste incineration production are reduced by 50% according to IDA2045.*

3. Biogas production

Biogas production in Denmark is commonly centralised with own co-digestion and upgrading facilities that directly inject renewable natural gas into the gas grid. A little over two-fold biogas production increase is expected by 2045 nationally in Denmark. Biogas usage in conversion technologies for electricity and heating cogeneration are crucial to supply renewable heat to DH systems. The increase in biogas generation aligns with projections of biomass potentials, signifying the upper limit achievable through the systematic utilization of various biomasses in the feedstock. This encompasses green agricultural waste, straw, wood, and heightened recyclability. The calculation involves deducting the organic share allocated for biogas from both industrial and residual waste. *Assuming this expansion as uniform across the nation, biogas production related CO_2 emission in the baseline is multiplied by a 2.13 factor in 2045.*

4. Industrial electrification

Another factoring element for CO_2 accountability is the industrial development as electrification replaces fossil fuels in industrial processes in Denmark. According to IDA2045, the increase of electricity demand does not only respond to electrification in industry but also to new critical electricity demand e.g., from hydrogen, electrofuel production, data centres. Fossil fuels will be replaced with electricity, solid biomass, and biogas in industry. Projecting the development of this projection at an industrial level, particularly at the CO_2 point source level, proves challenging due to the specificity inherent to each production process. This uncertainty is partly technical as emerging technologies to replace thermal and melting processes are not mature enough for large-scale deployment or remain costly, and sector integration strategies are difficult to predict. From the regulatory side, it can be predicted that newcoming reforms in the Danish carbon market i.e., The Danish Green Tax Reform could incentivize for industry to decarbonize through electrification and fuel substitution, incentivised by tax credits and green investment programs. The Green Industry Analysis (Energistyrelsen, 2020) project strategically tackles products and processes in specific industries in the nation. The study performed by the DEA in collaboration with industry and academia, shows technological solutions to convert large parts of the energy-related emissions from industry. It estimates the average emission saving that the electrification of the processes involved in determined production can provide. It adds with specific cases and processes pipelines in industrial decarbonization. Although these insights are given for a specific product in an industrial branch, they are taken as the most available estimate on feasible industrial decarbonizing available. *Each identified industrial branch used as examples in the study has been mapped and the emission reductions potentials have been discounted from initially calculated industrial CO_2 emissions.*

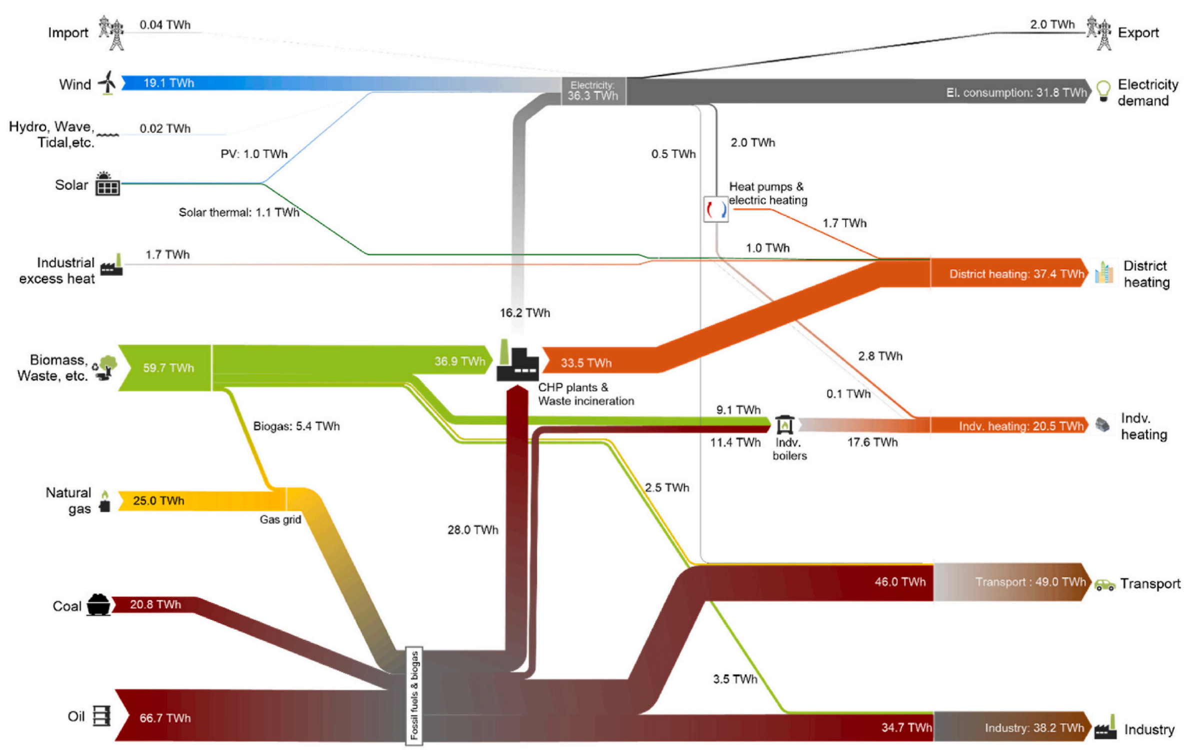

Fig. 15*IDA's Danish Energy System 2020 baseline scenario from* (Lund et al., 2021)

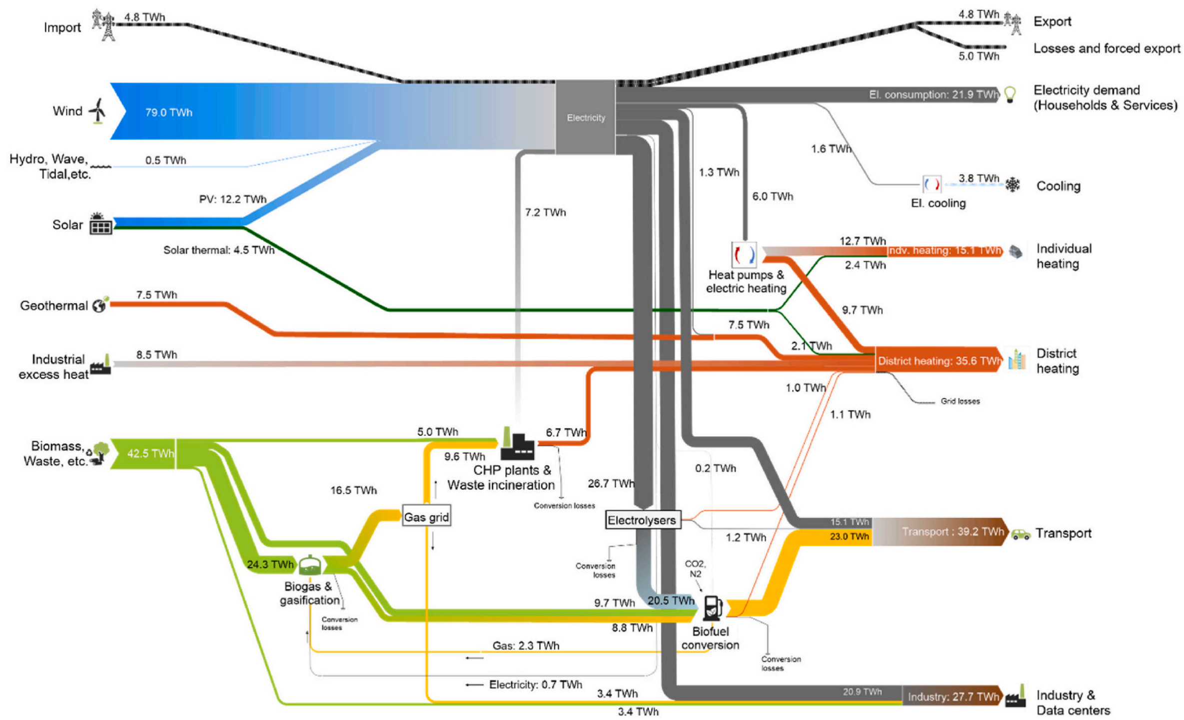

Fig. 16. *IDA's Smart Energy Denmark 2045 scenario from* (Lund et al., 2021). *Highlights the fossil fuel complete phase out and direct electrification of the heating and transport sector combined with e-fuel production.*

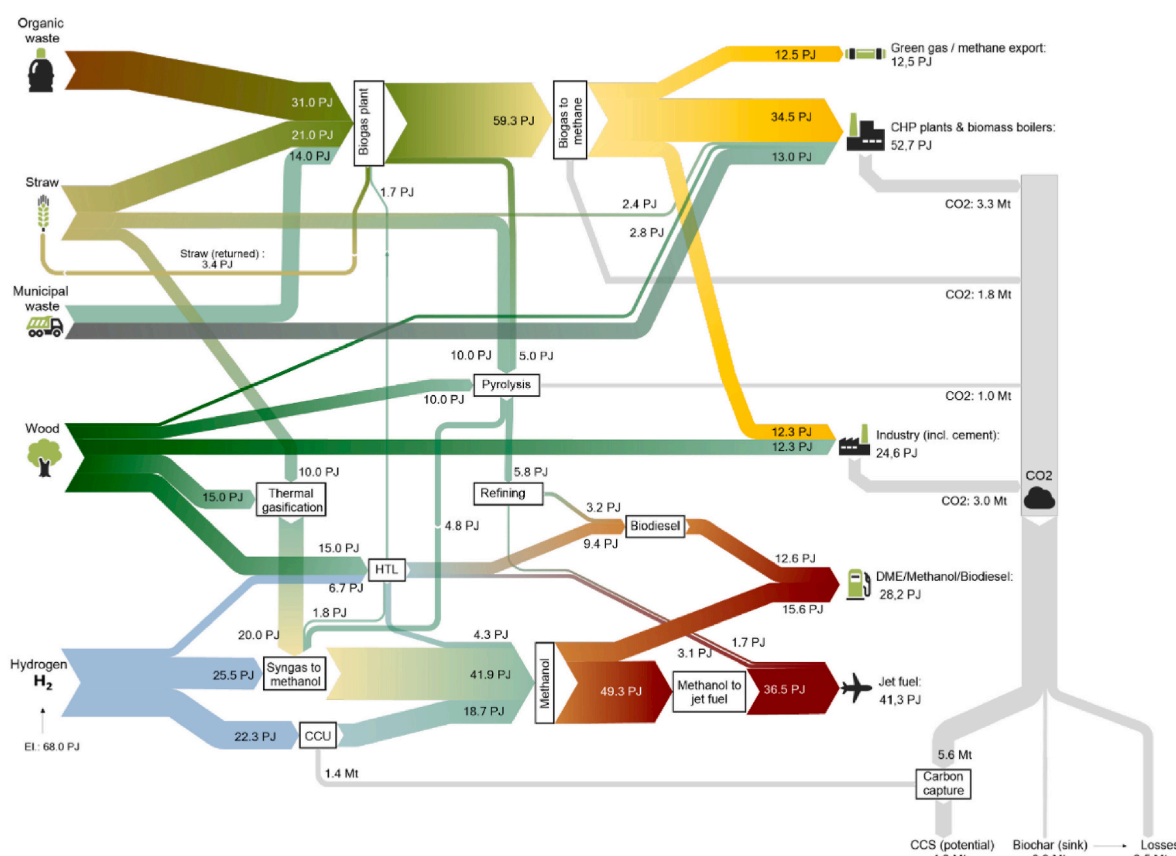

Fig. 17. *Overview of the use of biomass with biogas export and biogenic CCUS in the IDA's Smart Energy Denmark 2045 scenario from* (Lund et al., 2021).

Appendix B. Detailed TAC cost components

Table B1
TAC CAPEX and OPEX cost components.

Name	Mode	CAPEX	OPEX
Capture (CC)	Amine based PCC	CO_2 capture plant CO_2 compression and drying to Pipeline pressure Utilities (cooling water, electricity, steam, etc.) Integration costs to main plant Owner's cost (contingency)	Staffing Maintenance Service agreements Heat and electricity costs Make-up amine Caustic soda Waste disposal costs Variable maintenance costs
Transport (CT)	Truck	Semi-truck/semi-trailer/articulated lorry[2]	Driver costs Fuel consumption Fuel cost Truck annual maintenance Loading and unloading time
	Pipe[1]	Pipeline installation Cathodic protection and coating Sectionalisation valve @15 km Permitting costs and landowner compensation	Operation and maintenance costs of pipeline
	Ship	Ship unit	Ship fuel cost Ship operation and maintenance
Storage (CS)	Onshore	Injection plant Loading system without pipeline Injection wells	Base cost Onshore injection plant Loading system without pipeline Wells Decommissioning costs Energy costs Pre-FID costs Post closure monitoring (20 years)
	Near onshore/Offshore in depleted oil/gas field	Platform Injection plant Loading system without pipeline Injection wells	Base cost Platform Onshore injection plant Loading system without pipeline Wells Decommissioning costs Energy costs Pre-FID costs Post closure monitoring (20 years)
Intermediate storage (CIS)	At port	Insulated bullet tanks CO_2 transfer piping Marine loading arm Loading pumps CO_2 metering equipment and utilities	Operation and maintenance
	At site	Insulated bullet tanks CO_2 transfer piping Loading pumps CO_2 metering equipment and utilities	Operation and maintenance

1 Excludes pumping/compression energy cost in pipeline.
2 A truck that carries the freight in one or more semitrailers.
Truck and ship transport: Liquid phase CO_2 operating at ≈15 bar and at −28 °C.
Pipeline transport: Dense phase CO_2 operating at 15–30 °C and pressure max 150 bar.

Appendix C. Techno-economic components

Each of the cost projections used in the model are elaborated in this section.

- Carbon capture (CC)

This model factors the costs associated to the capture plant and the preparation of the CO_2 for its transportation. The capture cost includes compression costs for piping of CO_2 which amounts to 10% of the CAPEX. The model does not differentiate the preparation of CO_2 before transportation, resulting in the costs for liquefaction during trucking and shipping being equated to compression costs in the model. The capture costs database used are for amine based PCC retrofit 100 MW (th) WtE or biomass CHP plant and PCC retrofit 500 MW (th) biomass-fired boiler. Both costs are incorporated and projected to consider a generic framework for different CO_2 point sources and plant sizes. This makes it possible due to its potential integration through retrofitting into existing infrastructure with capturing modules in industrial production plants, power production, biogas or WtE facilities (Thellufsen and Wild, 2023). The total cost associated with the capture plant constitutes approximately 50% of the CC capital expenditure (CAPEX) which is omitted in quantifying capture costs for biogas production plants, assuming that these plants are equipped with operational upgrading facilities functioning as capture plants. For both facility types, Figure C1 and Figure C2 show the annualised cost projections with thresholds with the yearly captured CO_2 as the dependent variable.

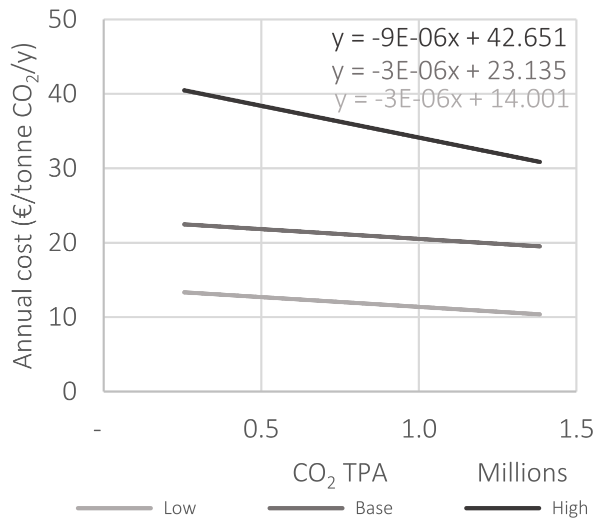

Fig. C1. Annual capture costs projections for non-biogas facilities.

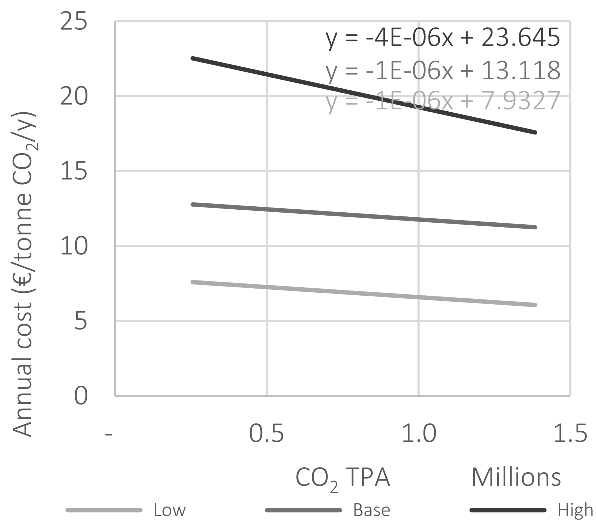

Fig. C2. Annual capture costs projections for biogas facilities.

- Carbon transport (CT)

The CO_2 transport costs tabulate the transport infrastructure capacity and the distance from the point source to the CO_2 terminal, given the transportation mode. The transport modes are trucking, shipping, and onshore and offshore piping for which the CO_2 must meet certain conditions on pressure, temperature, and dryness. Taking the transport capacity and distance, the model calculates the maximum amount of CO_2 that can be transported in a year per transport unit, i.e., one truck, ship, or single pipeline. The operation for the maximum amount of CO_2 calculation is assumed to be 24/7, nonetheless considering factors impacting this operation i.e., annual maintenance, loading/unloading and loading/sailing time, and average transport speed. The model then allocates the number of transport units required for transporting a given CO_2 quantity across a defined distance, calculating the associated costs accordingly.

The trucking costs consider the CO_2 transported in a liquid phase by tankers designed for operating at ≈15 bar and −28 °C with carrying capacity of 30 tonnes. figure C3 shows the annual cost projection for trucking with thresholds. In contrast, figure C4 portrays a combined plot showing a base cost of truck transport against the maximum yearly CO_2 transported over distance per transport unit.

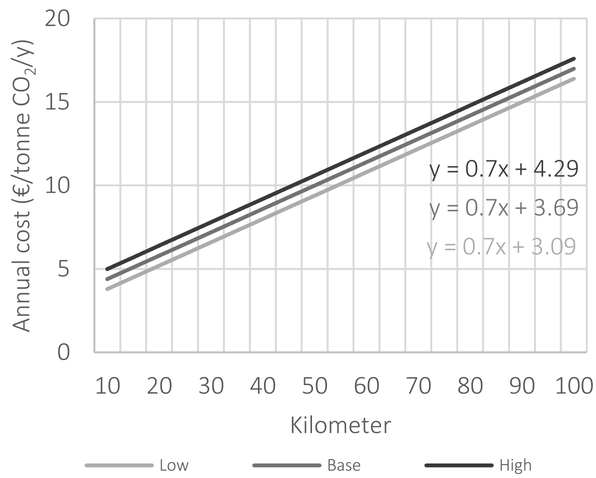

Fig. C3. Annual cost projections for CO2 truck transport.

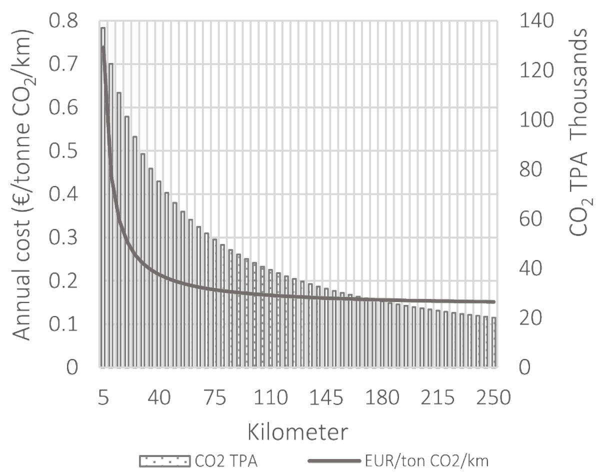

Fig. C4. Annual cost of trucking versus yearly CO_2 trucked over distance.

The shipping costs account for CO_2 transported in liquid form by ships operating at ~15 bar and −28°C. The DEA database provides costs for 4,000 and 10,000-tonne CO_2 ship capacities, with the maximum value for 10,000 tonnes (Kearns et al., 2021). This study projects costs for 1,000 and 2, 000-tonne CO_2 shiploads in Denmark, extrapolated from larger ships. Rail transport is unsuitable due to the spatial distribution of sources and the Danish rail network.Figure C5 shows annual shipping cost projections by ship capacity, while Figure C6 compares truck transport costs with maximum yearly CO_2 transported per unit.

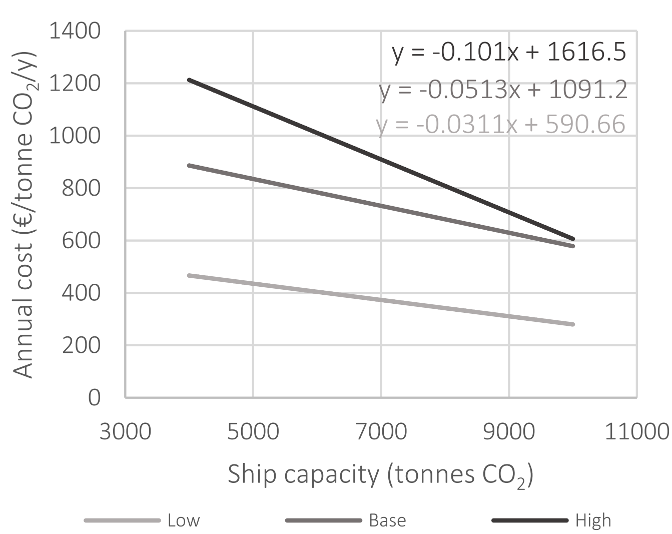

Fig. C5. Annual cost projections for CO_2 ship transport.

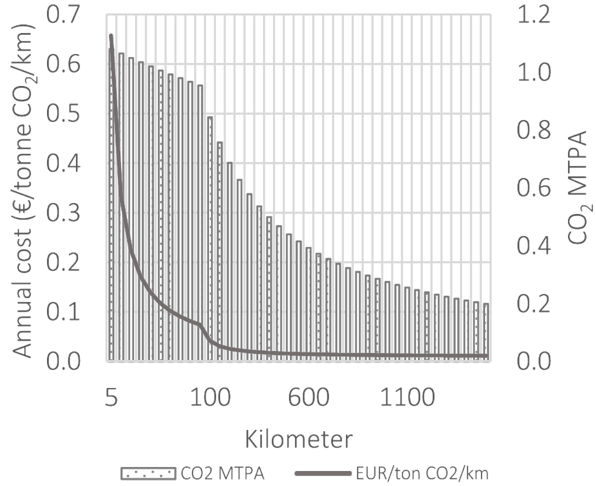

Fig. C6. Annual cost of shipping versus yearly CO_2 shipped over distance.

The pipeline costs consider CO_2 to be transported in a dense phase in pipeline dimensioned to operate at 150 bar and 15–30 °C, for both onshore and offshore transport at a 50% utilisation rate. Onshore piping costs for single-line pipelines ranging from 100 to 300 Diameter Nominal (DN) and offshore 300 DN piping are considered. All CO_2 piping infrastructure in the model is regarded as a new investment. Denmark current natural gas infrastructure may hold potential relevance; however, it is not considered in the model due to the lack of data concerning the adaptability and repurposing feasibility of this infrastructure and the cost associated with retrofitting it for CO_2 transport. Table C1 shows the annual cost projections for CO_2 pipe transport by type and yearly transportation capacity. Note that the prices are based on pipeline distances 50–100 km, hence the effect of the high cost at a short distance is not captured.

Table C1
Annual cost projections for CO_2 pipe transport.

Pipeline		DN	€/m/y		
Type	Capacity CO_2 TPA		Low	Base	High
Onshore	<100	100	15	20	27
	100k - 550k	150	30	41	53
	>550k	300	41	56	76
Offshore	>550k	300	64	89	153

- Carbon storage (CS)

Onshore, nearshore, and offshore infrastructure costs are considered for the CO_2 storage. The cost database includes capacities ranging from 1 to 5 MTPA storage capacity for all types of storage infrastructure. Similarly to the other transport modes, the database costs are used for the annual cost projection calculation for onshore, nearshore, and offshore CO_2 storage, as seen in Figure C7, Figure C8, and Figure C9, respectively, where the yearly CO_2 storage capacity functions as the dependent variable.

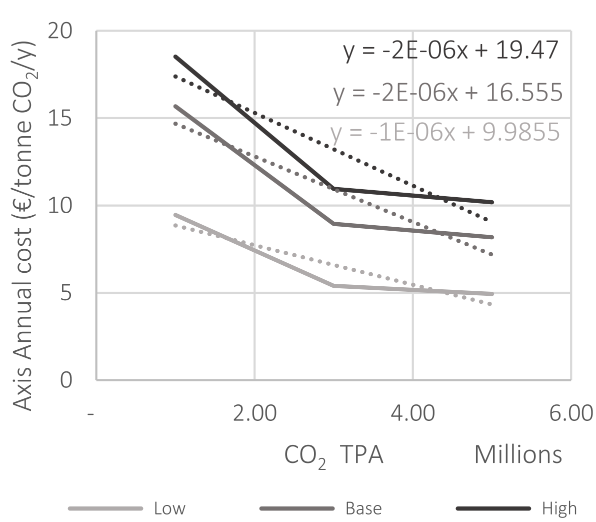

Fig. C7Annual cost projections for onshore CO_2 storage.

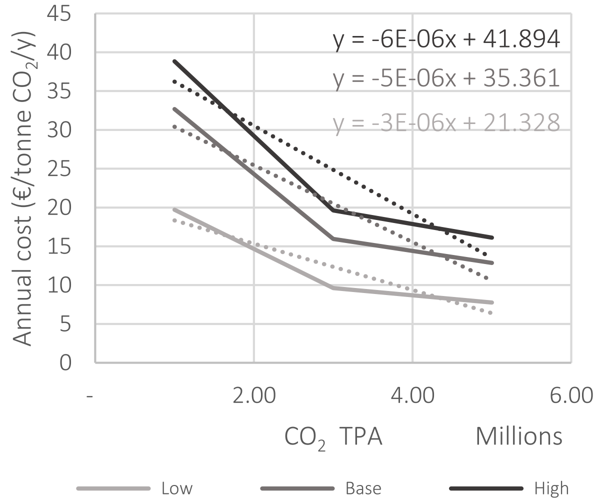

Fig. C8. Annual cost projections for nearshore CO_2 storage.

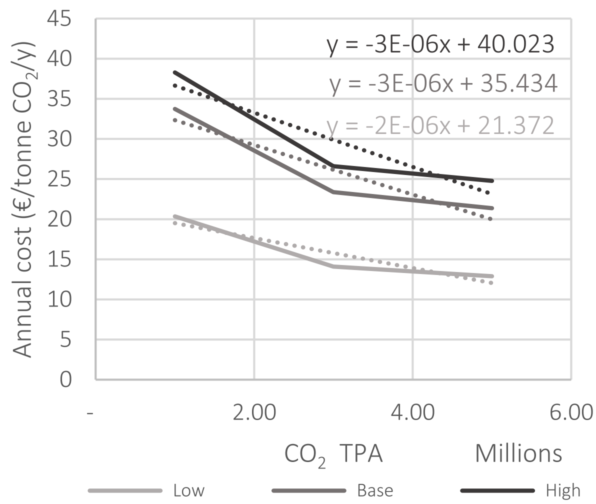

Fig. C9. Annual cost projections for offshore CO_2 storage.

- Carbon intermediate storage (CIS)

Storage facilities are considered for the carbon to be stored in terminals for it to be transported either by truck or ship. The storage capacities for projecting these terminal costs are for 3,00 and 14,000 tonnes CO_2 with varying storage hours for terminals at site and port terminals, assuming transport by truck is more cyclic than transport by ship due to the order of scale. When CO_2 pipeline transport is considered, no storage is added as a consistent flow of CO_2 is anticipated. Figure C10 and Figure C11 show the annualised base cost projections with thresholds with the yearly CO_2 stored in the terminal as the dependent variable.

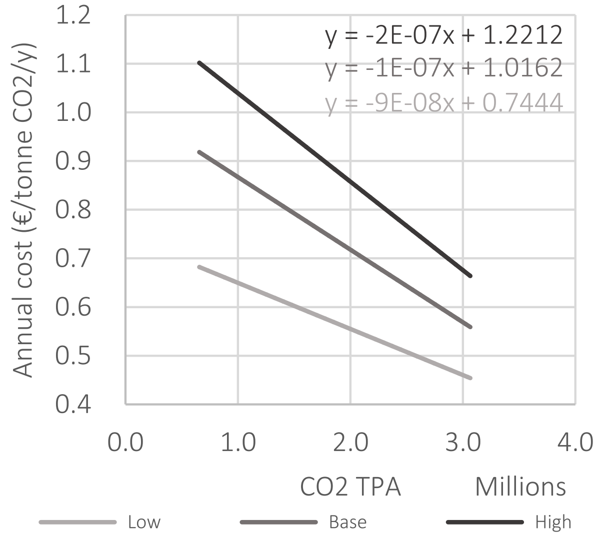

Fig. C10Annual costs projections for CO2 terminals at site.

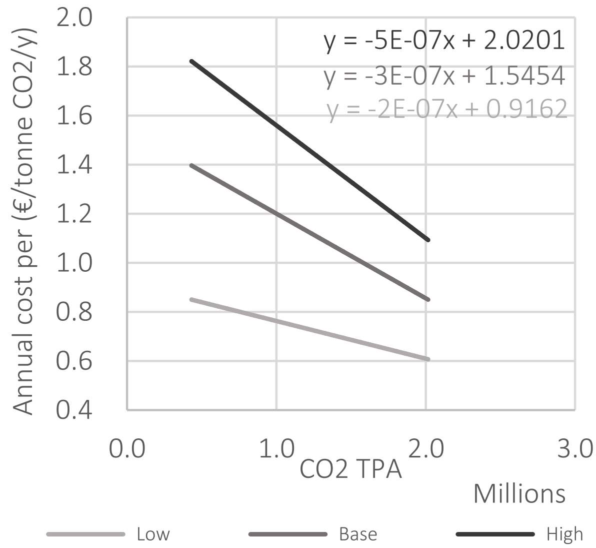

Fig. C11. Annual costs projections for CO_2 terminals at port.

References

Al-Shargabi, M., Davoodi, S., Wood, D.A., Rukavishnikov, V.S., Minaev, K.M., 2022. Carbon dioxide applications for enhanced oil Recovery assisted by nanoparticles: recent developments. In *ACS omega* (vol. 7, issue 12). https://doi.org/10.1021/acsomega.1c07123.

Bang, A., Moreno, D., Lund, H., Nielsen, S., 2024. Regional CCUS Strategies in the Context of a Fully Decarbonized Society. [Manuscript Submitted for Publication].

Becattini, V., Gabrielli, P., Antonini, C., Campos, J., Acquilino, A., Sansavini, G., Mazzotti, M., 2022. Carbon dioxide capture, transport and storage supply chains: optimal economic and environmental performance of infrastructure rollout. Int. J. Greenh. Gas Control 117. https://doi.org/10.1016/j.ijggc.2022.103635.

Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., Fuss, S., Galindo, A., Hackett, L.A., Hallett, J.P., Herzog, H.J., Jackson, G., Kemper, J., Krevor, S., Maitland, G.C., Matuszewski, M., Metcalfe, I.S., Petit, C., Mac Dowell, N., 2018. Carbon capture and storage (CCS): the way forward. In: Energy and Environmental Science. Royal Society of Chemistry, pp. 1062–1176. https://doi.org/10.1039/c7ee02342a.

Carr, E.W., Shirazi, Y., Parsons, G.R., Hoagland, P., Sommerfield, C.K., 2018. Modeling the economic value of blue carbon in Delaware estuary wetlands: historic estimates and future projections. J. Environ. Manag. 206 https://doi.org/10.1016/j.jenvman.2017.10.018.

Chen, J.M., Thomas, S.C., Yin, Y., Maclaren, V., Liu, J., Pan, J., Liu, G., Tian, Q., Zhu, Q., Pan, J.J., Shi, X., Xue, J., Kang, E., 2007. Enhancing forest carbon sequestration in China: toward an integration of scientific and socio-economic perspectives. J. Environ. Manag. 85 (3) https://doi.org/10.1016/j.jenvman.2006.08.019.

Chen, S., Liu, J., Zhang, Q., Teng, F., McLellan, B.C., 2022. A critical review on deployment planning and risk analysis of carbon capture, utilization, and storage (CCUS) toward carbon neutrality. In Renewable and Sustainable Energy Reviews (Vol. 167). https://doi.org/10.1016/j.rser.2022.112537.

Connolly, D., Lund, H., Mathiesen, B.V., 2016. Smart Energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew. Sustain. Energy Rev. 60, 1634–1653.

Cordova, S.S., Gustafsson, M., Eklund, M., Svensson, N., 2022. Potential for the valorization of carbon dioxide from biogas production in Sweden. J. Clean. Prod. 370, 133498. https://doi.org/10.1016/J.JCLEPRO.2022.133498.

Cuéllar-Franca, R.M., Azapagic, A., 2015. Carbon capture, storage and utilisation technologies: a critical analysis and comparison of their life cycle environmental impacts. J. CO2 Util. 9 https://doi.org/10.1016/j.jcou.2014.12.001.

Dalhoff, F., Klinkby, L., Sørensen, A.T., Bernstone, C., Frykman, P., Andersen, C., Christensen, N.P., 2011. CCS demo Denmark: the vedsted case. Energy Proc. 4, 4704–4710. https://doi.org/10.1016/j.egypro.2011.02.432.

Das, A., Saini, V., Parikh, K., Parikh, J., Ghosh, P., Tot, M., 2023. Pathways to net zero emissions for the Indian power sector. Energy Strategy Rev. 45 https://doi.org/10.1016/j.esr.2022.101042.

Dataforsyningen, 2023. Dansk vejnet. https://dataforsyningen.dk/data.

Ding, T., Steubing, B., Achten, W.M.J., 2023. Coupling optimization with territorial LCA to support agricultural land-use planning. J. Environ. Manag. 328, 116946. https://doi.org/10.1016/J.JENVMAN.2022.116946.

Dods, M.N., Kim, E.J., Long, J.R., Weston, S.C., 2021. Deep CCS: moving beyond 90% carbon dioxide capture. Environ. Sci. Technol. 55 (13) https://doi.org/10.1021/acs.est.0c07390.

Dziejarski, B., Krzyżyńska, R., Andersson, K., 2023. Current status of carbon capture, utilization, and storage technologies in the global economy: a survey of technical assessment. In: Fuel. https://doi.org/10.1016/j.fuel.2023.127776, 342.

Energistyrelsen, 2020. Grøn industrianalyse rapport. Potentialer og barrierer for fossiludfasning i industri.

Energistyrelsen, 2021. Liste over biogasproducenter i Danmark. https://ens.dk/sites/ens.dk/files/Bioenergi/liste_over_biogasanlaeg_i_dk.pdf.

Energistyrelsen, 2023a. Standardfaktorer for Brændværdier Og CO2emissionsfaktorer Til Brug for Rapporteringsåret 2022.

Energistyrelsen, 2023b. Punktkilder til CO2 – potentialer for CCS og CCU 2022-opdatering. https://ens.dk/sites/ens.dk/files/CCS/punktkilder_til_co2_-_potentialer_for_ccs_og_ccu_2022-opdatering.pdf.

Energistyrelsen, 2023c. Energiproducenttællingen for 2022. https://ens.dk/sites/ens.dk/files/Energikrav/resultat_af_energiproducenttaellingen_for_2022.pdf.

Energistyrelsen, 2023d. Tilladelser til efterforskning og lagring af CO2 og miljøhøringer. https://tinyurl.com/hxjdr457.

Energy Supply, 2023. Aalborg Portland i storaftale: sender 400.000 tons CO2 til lagring. https://tinyurl.com/my59zaxf.

Erhvervsstyrelsen, 2022. Det centrale virksomhedsregister. https://erhvervsstyrelsen.dk/hent-oplysninger-fra-cvr.

Esri, 2023a. ArcGIS Pro. Version 3.1.0. In: Environmental Systems Research Institute, Inc.

Esri, 2023b. Closest facility analysis layer. https://pro.arcgis.com/en/pro-app/3.1/help/analysis/networks/closest-facility-analysis-layer.htm.

Esri, 2023c. Network path planner toolbox. https://doc.arcgis.com/en/arcgis-solutions/11.2/reference/introduction-to-network-path-planner.htm.

European Environment Agency, 2020. European pollutant release and transfer register (E-PRTR), v18. https://tinyurl.com/4ywv4fd9.

Fasihi, M., Efimova, O., Breyer, C., 2019. Techno-economic assessment of CO 2 direct air capture plants. J. Clean. Prod. 224 https://doi.org/10.1016/j.jclepro.2019.03.086.

Ferrada, F., Babonneau, F., Homem-de-Mello, T., Jalil-Vega, F., 2023. The role of hydrogen for deep decarbonization of energy systems: a Chilean case study. Energy Pol. 177 https://doi.org/10.1016/j.enpol.2023.113536.

Food & Bio Cluster Denmark, 2020. Biogas Production: Insights and Experiences from the Danish Biogas Sector Report.

Forsyning, Aalborg, 2023. Det haster med en aftale om at fremskynde udfasning af kul på Nordjyllandsværket. https://tinyurl.com/yc89zwvs.

Garcia-Gusano, D., Espegren, K., Lind, A., Kirkengen, M., 2016. The role of the discount rates in energy systems optimisation models. In Renewable and Sustainable Energy Reviews (Vol. 59). https://doi.org/10.1016/j.rser.2015.12.359.

Geus, 2020. Capture, Storage and Use of CO2 (CCUS).

Global Ccs Institute, 2021. Global status of CCS 2021 report. www.globalccsinstitute.com/wp-content/uploads/2021/10/2021-Global-Status-of-CCS-Report_Global_CCS_Institute.pdf.

Gogoi, A., Ahirwal, J., Sahoo, U.K., 2022. Evaluation of ecosystem carbon storage in major forest types of Eastern Himalaya: implications for carbon sink management. J. Environ. Manag. 302 https://doi.org/10.1016/j.jenvman.2021.113972.

Greenhub Denmark, 2023. CCUS klynge nordjylland: CO2 vision project report. https://greenhubdenmark.dk/.

He, G., Mallapragada, D.S., Bose, A., Heuberger-Austin, C.F., Gençer, E., 2021. Sector coupling: via hydrogen to lower the cost of energy system decarbonization. Energy Environ. Sci. 14 (9) https://doi.org/10.1039/d1ee00627d.

Huang, B., Bühler, F., Müller Holm, F., 2015. Industrial Energy Mapping: THERMCYC WP6. Technical University of Denmark.

Iea, 2023. CO2 emissions in 2022 analysis. Global energy. https://www.iea.org/reports/co2-emissions-in-2022.

Ieaghg, 2019. Towards Zero Emissions CCS in Power Plants Using Higher Capture Rates or Biomass.

Ipcc, 2022. Climate change 2022: mitigation of climate change report. www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf.

Ipcc, 2023. Climate change 2023 synthesis report. In IPCC, 2023 (vol. 13, issue 3). https://www.ipcc.ch/report/sixth-assessment-report-cycle/.

Irena, 2022. World energy transitions outlook 2022: 1.5°C Pathway Report. In: In International Renewable Energy Agency. https://www.irena.org/publications/2022/mar/world-energy-transitions-outlook-2022.

Jakobsen, J., Bysveen, M., Vågenes, E., Eickhoff, C., Mikunda, T., Neele, F., Brunner, L., Heffron, R., Schumann, D., Downes, L., Hanstock, D., 2017. Developing a pilot case and modelling the development of a large European CO2 transport infrastructure -the GATEWAY H2020 project. Energy Proc. 114 https://doi.org/10.1016/j.egypro.2017.03.1820.

Jha, A., Ravuru, V., Yadav M Mandal, S.D.A., 2021. A critical analysis of CO2 capture technologies. Hydrocarb. Process.

Johnson, N., Parker, N., Ogden, J., 2014. How negative can biofuels with CCS take us and at what cost? Refining the economic potential of biofuel production with CCS using spatially-explicit modeling. Energy Proc. 63, 6770–6791. https://doi.org/10.1016/j.egypro.2014.11.712.

Karlsson, S., Normann, F., Johnsson, F., 2024. Cost-optimal CO2 capture and transport infrastructure—a case study of Sweden. Int. J. Greenh. Gas Control 132, 104055. https://doi.org/10.1016/J.IJGGC.2023.104055.

Kearns, D., Liu, H., Consoli, C., 2021. Technology Readiness and Costs of CCS - Global CCS Institute. In Global CCS Insitute (Issue March).

Kim, C., Yoo, C.J., Oh, H.S., Min, B.K., Lee, U., 2022. Review of carbon dioxide utilization technologies and their potential for industrial application. J. CO2 Util. 65 https://doi.org/10.1016/j.jcou.2022.102239.

Kouri, S., Tsupari, E., Kärki, J., Teir, S., Sormunen, R., Arponen, T., Tuomaala, M., 2017. The potential for CCUS in selected industrial sectors - summary of concept evaluations in Finland. Energy Proc. 114 https://doi.org/10.1016/j.egypro.2017.03.1778.

Li, H., Tan, Y., Ditaranto, M., Yan, J., Yu, Z., 2017. Capturing CO2 from biogas plants. Energy Proc. 114, 6030–6035. https://doi.org/10.1016/J.EGYPRO.2017.03.1738.

Lund, H., Østergaard, P.A., Connolly, D., Mathiesen, B.V., 2017. Smart energy and smart energy systems. Energy 137, 556–565. https://doi.org/10.1016/j.energy.2017.05.123.

Lund, H., Vad Mathiesen, B., Zinck Thellufsen, J., Sorknæs, P., Chang, M., Stunge Kany, M., Ridjan Skov, I., 2021. IDAs Klimasvar 2045: Sådan bliver vi klimaneutrale. https://vbn.aau.dk/ws/portalfiles/portal/413672453/IDAs_klimasvar_2045_ver_02062021.pdf.

Lund, H., Skov, I.R., Thellufsen, J.Z., Sorknæs, P., Korberg, A.D., Chang, M., Mathiesen, B.V., Kany, M.S., 2022a. The role of sustainable bioenergy in a fully decarbonised society. Renew. Energy 196. https://doi.org/10.1016/j.renene.2022.06.026.

Lund, H., Thellufsen, J.Z., Sorknæs, P., Mathiesen, B.V., Chang, M., Madsen, P.T., Kany, M.S., Skov, I.R., 2022b. Smart energy Denmark. A consistent and detailed strategy for a fully decarbonized society. Renew. Sustain. Energy Rev. 168 https://doi.org/10.1016/j.rser.2022.112777.

Luo, S., Hu, W., Liu, W., Xu, X., Huang, Q., Chen, Z., Lund, H., 2021. Transition pathways towards a deep decarbonization energy system—a case study in Sichuan, China. Appl. Energy 302. https://doi.org/10.1016/j.apenergy.2021.117507.

Mathiesen, B.V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P.A., Möller, B., Nielsen, S., Ridjan, I., Karnøe, P., Sperling, K., Hvelplund, F.K., 2015. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl. Energy 145, 139–154. https://doi.org/10.1016/j.apenergy.2015.01.075.

Middleton, R.S., Bielicki, J.M., 2009. A scalable infrastructure model for carbon capture and storage: SimCCS. Energy Policy, 37(3). https://doi.org/10.1016/j.enpol.2008.09.049.

Morbee, J., Serpa, J., Tzimas, E., 2012. Optimised deployment of a European CO2 transport network. Int. J. Greenh. Gas Control 7, 48–61. https://doi.org/10.1016/J.IJGGC.2011.11.011.

Neele, F., Koenen, M., Van Deurzen, J., Seebregts, A., Groenenberg, H., Thielemann, T., 2011. Large-scale CCS transport and storage networks in NorthNorth-west and central Europe. Energy Proc. 4, 2740–2747. https://doi.org/10.1016/J.EGYPRO.2011.02.176.

Northern Lights Consortium, 2023. About the longship project - northern Lights. https://Norlights.Com/about-the-Longship-Project/.

Ozkan, M., Akhavi, A.A., Coley, W.C., Shang, R., Ma, Y., 2022. Progress in carbon dioxide capture materials for deep decarbonization. In Chem (Vol. 8, Issue 1). https://doi.org/10.1016/j.chempr.2021.12.013.

Paul, C., Bartkowski, B., Dönmez, C., Don, A., Mayer, S., Steffens, M., Weigl, S., Wiesmeier, M., Wolf, A., Helming, K., 2023. Carbon farming: are soil carbon certificates a suitable tool for climate change mitigation? J. Environ. Manag. 330, 117142. https://doi.org/10.1016/J.JENVMAN.2022.117142.

Aalborg Portland, 2023. Aalborg Portland etablerer nyt pilotanlæg til CO2-fangst: kan reducere energiforbruget ved CCUS markant og sikre bedre udnyttelse af CO2. Aalborg Portland Cement Holding. https://tinyurl.com/5n753arw.

Ravaioli, G., Domingos, T., Teixeira, F.M., 2023. Data-driven agent-based modelling of incentives for carbon sequestration: the case of sown biodiverse pastures in Portugal. J. Environ. Manag. 338 https://doi.org/10.1016/j.jenvman.2023.117834.

Renewable Energy Directive, 2018. (2018/2001/EU).

Ritchie, H., Roser, M., Rosado, P., 2020. CO_2 and greenhouse gas emissions. OurWorldInData.Org. https://ourworldindata.org/co2-and-greenhouse-gas-emissions.

Simão, A., Densham, P.J., Muki Haklay, M., 2009. Web-based GIS for collaborative planning and public participation: an application to the strategic planning of wind farm sites. J. Environ. Manag. 90 (6) https://doi.org/10.1016/j.jenvman.2007.08.032.

State of Green, 2022. Carbon capture, utilisation, and storage. Picking the high-hanging fruits of CO2 mitigation.

Storrs, K., Lyhne, I., Drustrup, R., 2023. A comprehensive framework for feasibility of CCUS deployment: a meta-review of literature on factors impacting CCUS deployment. Int. J. Greenh. Gas Control 125. https://doi.org/10.1016/j.ijggc.2023.103878.

The Danish Energy Agency, 2019. Map of CHP and power plants with solid biofuels. https://ens.dk/sites/ens.dk/files/Statistik/chp_and_power_plants_-_solid_biofuels.pdf.

The Danish Energy Agency, 2020. Map of biogas plants in Denmark. Plants in operating and under establishment. https://ens.dk/sites/ens.dk/files/Bioenergi/biogas_2020_06_eng.pdf.

The Danish Energy Agency, 2023a. Biogas in Denmark. https://ens.dk/en/our-responsibilities/bioenergy/biogas-denmark.

The Danish Energy Agency, 2023b. Map of existing biogas plants and biomethane production to the gas system. https://ens.dk/sites/ens.dk/files/Bioenergi/map_of_biogas_plants_denmark.pdf.

The Danish Energy Agency, 2023c. Technology data for carbon capture, transport and storage. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-carbon-capture-transport-and.

Thellufsen, J.Z., Wild, C., 2023. LSICC deliverable 1-carbon capture technology overview. https://vbn.aau.dk/ws/portalfiles/portal/538558176/Deliverable_1.pdf.

Thellufsen, J.Z., Lund, H., Sorknæs, P., Østergaard, P.A., Chang, M., Drysdale, D., Nielsen, S., Djørup, S.R., Sperling, K., 2020. Smart energy cities in a 100% renewable energy context. Renew. Sustain. Energy Rev. 129 https://doi.org/10.1016/j.rser.2020.109922.

Tumara, D., Uihlein, A., Hidalgo Gonzalez, I., 2024. Shaping the future CO2 transport network for Europe (Issue KJ-NA-31-835-EN-N (online)). Publications Office of the European Union. https://doi.org/10.2760/582433.

U.S. Energy Information Administration, 2023. International energy outlook 2023 report. In EIA. https://www.iea.org/reports/world-energy-outlook-2023.

van den Broek, M., Brederode, E., Ramírez, A., Kramers, L., van der Kuip, M., Wildenborg, T., Faaij, A., Turkenburg, W., 2009. An integrated GIS-MARKAL toolbox for designing a CO2 infrastructure network in The Netherlands. Energy Proc. 1 (1), 4071–4078. https://doi.org/10.1016/J.EGYPRO.2009.02.214.

Victoria, M., Zhu, K., Brown, T., Andresen, G.B., Greiner, M., 2020. Early decarbonisation of the European energy system pays off. Nat. Commun. 11 (1) https://doi.org/10.1038/s41467-020-20015-4.

Wang, W., Rao, L., Wu, X., Wang, Y., Zhao, L., Liao, X., 2021. Supercritical carbon dioxide applications in food processing. In food engineering reviews (vol. 13, issue 3). https://doi.org/10.1007/s12393-020-09270-9.

Wildenborg, T., Loeve, D., Neele, F., 2022. Large-scale CO2 transport and storage infrastructure development and cost estimation in The Netherlands offshore. Int. J. Greenh. Gas Control 118, 103649. https://doi.org/10.1016/J.IJGGC.2022.103649.

Wu, Q., Lin, Q., Yang, Q., Li, Y., 2022. An optimization-based CCUS source-sink matching model for dynamic planning of CCUS clusters. Greenhouse Gases: Sci. Technol. 12 (4) https://doi.org/10.1002/ghg.2159.

Zhu, L., Duan, H.B., Fan, Y., 2015. CO2 mitigation potential of CCS in China - an evaluation based on an integrated assessment model. J. Clean. Prod. 103 https://doi.org/10.1016/j.jclepro.2014.08.079.